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THE NATIONAL SHIPBUILDING RESEARCH PROGRAM

FABRICATION ACCURACY
THROUGH DISORTION CONTROL
IN SHIPBUILDING

PANEL SP-7 REPORT
FOR PROJECT 07-87-02

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A WORD ABOUT THE NSRP:

The National Shipbuilding Research Program (NSRP) has been engaged in research related to improvements in shipbuilding in the U. S. since 1973. The program is a cooperative effort involving shipyards both commercial and Naval, and related industries and educational institutions.

Since the inception of the program in 1973, R&D projects have been performed which have contributed significantly to shipbuilding in the areas of facilities, environmental issues, outfitting and production aids, design and production integration, human resources innovations, training, coatings and flexible automation. A library and bibliography of NSRP reports is maintained at the University of Michigan, Transportation Research Institute, Ann Arbor, Michigan.

The program is carried out under not-for-profit contracts and cooperative agreements funded by the U. S. Navy and the Maritime Administration.

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The successful completion of this project would not have been possible without the support and cooperation of many people. Particular appreciation is acknowledge to those at Ingalls Shipbuilding including O. J. Davis, SP-7 Program Manager and L. G. Kvidahl, Chief Welding Engineer for their direction and support during this project, as well as R. W. McClellan And T. R. Warren, Welding Engineers, and W. J. Bryant, Welding Analyst for their assistance in testing. Additional appreciation is given to Mr. D. Houston, Engineering Department, St. John Shipbuilding, St. John, N.B., Canada for his assistance in the visit to St. John and those at Elevating Boats, Inc., Poydras, LA. for allowing the review of their stress relief efforts.

FOREWORD

This SP-7 project report was performed by the "Accuracy Control" group at the shipyard of Ingalls Shipbuilding, Inc. in Pascagoula, Mississippi under the leadership of Ron Besselievre and Lee Norton.

Duringthe time of performance of the task, no less than 12 major ships were in various stages of construction in the shipyard including 3 LHD's, 6 Aegis cruisers and 1 DDG 51 Arleigh Burke class destroyer. During that time, one LHD and three cruisers were completed.

The fact that the work of the project was being done by the group while simultaneously supporting shipyard operations presented both difficulties and opportunities. Not the least of the problems were the requirements of both tasks on the time and energy of the engineers. On the other hand, there was the positive advantage that over 100 tons of aluminum and steel was being cut into thousands of piece parts, fitted and welded into modules and integrated into ship structures. This situation made it possible for them to gain access to cutting and welding operations of large numbers of plates, beams and subassemblies, the like of which could hardly ever have been measured except in a working shipyard environment. The shipyard production situation also allowed them to keep in perspective not only the need for distortion control technology which is technically efficacious but which is cost effective with respect to manhour requirements and also practical in implementation.

One of the principal objectives of the task was to acquire and report empirical data on some of the distortion control and correction techniques which are in use, but, for which, quantitative data in non-existent or difficult to find.

The materials and processes used and the types of deformations measured are typical of those which are used and which present distortion problems in virtually all shipyards. Some of the topics covered include: Beams which were deflanged by oxy-gas cutting in preparation for structures, large inner bottom plate and beam structures being installed within the shell of the hull, deck and bulkhead panels which had bulges and buckles and other typical distortion control problem areas. The fact that these assemblies were able to be measured while in the process of growing into a ship is a bonus of this project.

An informative explanation and description of the fundamental mechanisms of distortions caused by welding and heating is presented in the report prior to going into the details of the experiments and measurements which were performed. It will be seen that those same causative mechanisms, when controlled, can be used as the basis for corrective procedures, as, for example, in line heating.

An effort was made in the project to acquire data on the effects of vibratory energy input on distortions due of welding, and that data is presented. Those experiments did not yield results sufficiently definitive to justify drawing any broad conclusions on that approach to stress relief and distortion control. It is clear that considerable experimentation and testing beyond the scope of this project would be needed to quantitatively evaluate the assertions of advocates of resonant and sub-resonant vibraton as a means of stress relief and distortion control.

Measurements were made to develop hard data on approaches to distortion prevention and correction which are of primary interest to shipbuilders including: pre-heating, backsetting of large panels while welding in place, backstepping and staggering the sequence of welding, use of water spray while oxy-gas cutting to deflange I-beams, and induction straightening. On each of these subjects, data is presented with a discussion of the methods used and a statistical analysis of the results. In addition, an appendix was added to provide a summary and discussion of the statistical methods used in analysis of the empirical data reported.

Distortion control in large complex, welded structures is a large and complex problem. No single technique is available to resolve all or even most of the problems. The principle objectives of this project was to provide quantitative, real-world data on some of the approaches to distortion control and to share that data. With the compiling and distribution of this report those objectives have been met. It is hoped that study of the report will stimulate further efforts to make unwanted deformations in welded ship structures predictable, correctable and eventually preventable.

O J Davis 10/22/90

O. J. Davis
SP-7 Program Manager

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1.0 Introduction

In ship construction, as in nearly all manufacturing industries of such a complex nature, the reduction of rework provides a significance opportunity for improving productivity. To accomplish this improvement, parts at each manufacturing stage must be made accurately so that correction in following stages is not necessary.

In many industries worldwide, statistical control methods are being used to obtain these accuracies. Interim processes that produce these parts are being placed into a measured state of control. Normally achieved accuracies are being defined. Systemic causes for inaccuracy are being identified. corrections instituted, and the effects of these corrections determined . In this fashion, the accuracy of parts and reduction of rework are being achieved in an organized, methodical manner that lends itself towards continual improvement.

Distortion from welding and burning processes is a systemic problem common to all shipbuilders. Because of the extensive use of welding and burning processes in nearly all stages of construction, the cost impact of distortion is substantial This impact appears iv not only the straightening costs necessary to remove the distortion, but also (and probably many times more costly) the increased efforts required in fitting distorted pieces. additionally, welding cost may be increased . The added welding costs that result from poorly fit pieces may in many cases be traced to distortion in the pieces at fitup.

In most situations, distortion may be significantly reduced or even eliminated through use of a variety of control methods. Thus, just as the dimensional size of parts may be controlled to minimize the accumulation of tolerances and

resulting rework; occurances, the distorted configuration of parts may be similarly controlled. Distortion and the added fitting, welding and straightening costs that go with it need not be passed from one stage to another. From this viewpont, the added costs from distortion must be considered as "rework" .

The application of distortion control cannot be left to the welder alone. In fact, too often the welder is blamed for distortion effects that are the result of choices in previous stages. For example, the design configuration of the weldment, design of joints and weld sizes, planned sequence of assembly, cut accuracy of parts, and fitup accuracy are all factors affecting the part distortion in which the welder normally has no input.

Instead , each individual involved at each stage in the design, planning and construction of a part must be responsible for minimizing its distortion. Proper application of distortion control must start with the design effort and continue through the final weldout of the product.

2.0 Approach

The objective of this report was to identify and discuss the various methods for reducing distortion in shipbuilding. including testing of some specified methods. This was accomplished through a review of current literature on this subject. observations of practices in-yard, and then testing of some selected distortion control methods, including:

- application of resonant vibration during shielded metal arc welding of Dutt welds
- presetting of flat innerbottom units
- backtep and wandering weld sequencing versus continuous flux core arc welding of butt welds
- preheating of submerged arc welded panel butt welds
- application of water coolant to I-beam flange stripping operation
- induction straightening of thinner plating.

In testing of methods, it is sometimes difficult to establish whether the differences in the test samples are the result of actual differences in the methods being tested or simply variations inherent in the sampling effort. For this reason, statistical methods were applied to establish the confidence level at which test conclusions could be made. To assist in the understanding of these resultsy the Appendix provides a brief description of the statistical methods used.

3.0 Weld Distortion : Heated Bar Analogy

Weld distortion and residual stresses occur from the restraint imposed on the weld as it tends to cool and contract. The most common analogy for describing this mechanism is that of a heated bar.

When a bar is uniformly heated, as in Figure 15 it will expand in all directions. When cooled, the bar will contract uniformly in all directions and return to its original dimensions.

If this bar is restrained while heating, as in Figure 2, then it is prevented from expanding laterally. The same volume expansion must occur, however, so that it expands a greater amount vertically. As the bar cools, it again contracts uniformly in all directions. This contraction, however, does not return the bar to its original dimensions. It is narrower laterally and thicker vertically. It is said to be "permanently upset" or "deformed".

What would happen if this bar were restrained whils cooling? If restrained, then contraction would be prevented . Tensile stresses would develop that could eventualy equal the yield stress of the material.

The stress and strain effects on this par as it is heated and cooled are analogous to these occuring in a welded joint. As the weld metal is deposited and begins to solidify, it is at its maximum volume. As the weld metal cools, it tends to contract but is somewhat restrained by the adjacent base metal. Tensile stresses are developed.

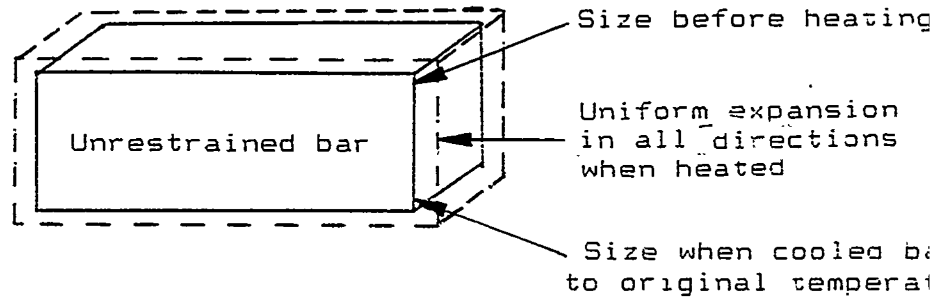


Figure 1. Dimensional change of unrestrained bar when heated and then cooled back to original temperature

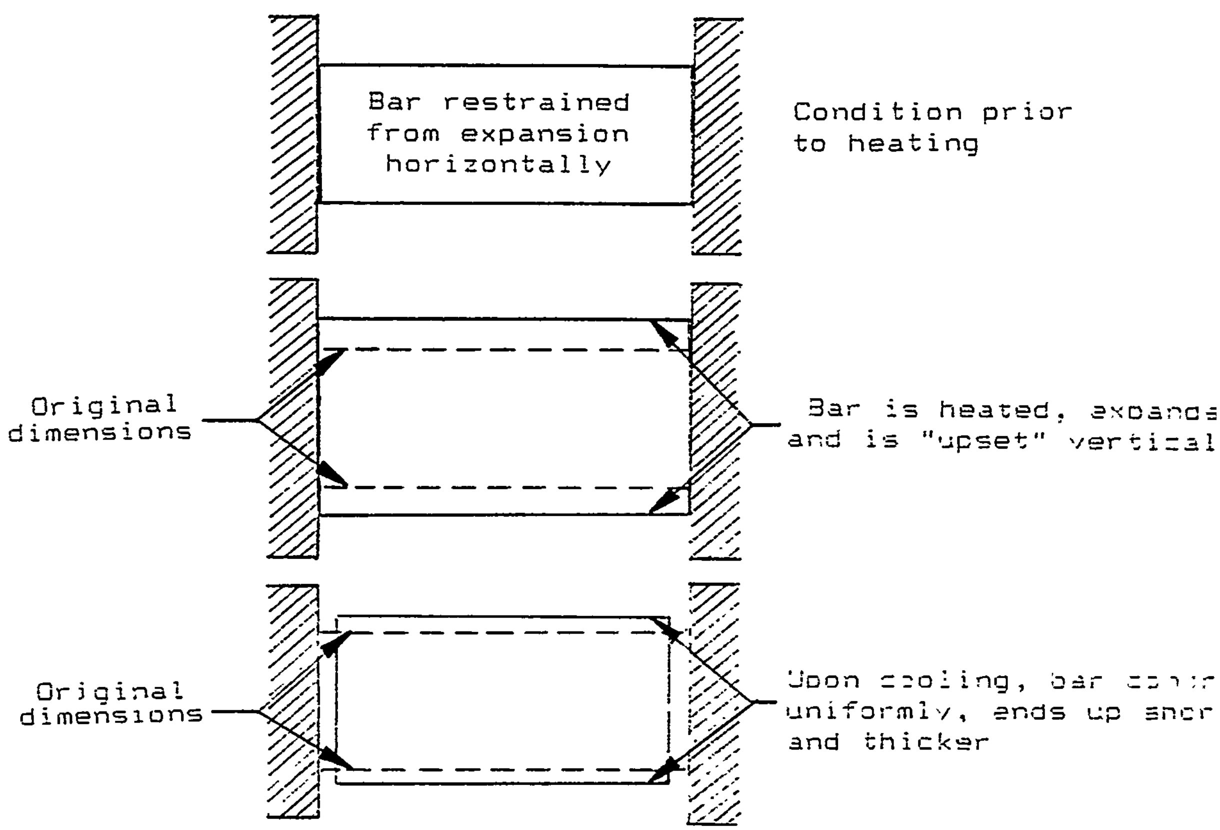


Figure 2. Dimensional change of bar restrained from expansion horizontally when heated and then cooled back to original temperature

If the adjacent base metal is restrained from moving (by clamps, dogs, turnbuckles,etc.), then the tensile stresses developed may eventually reach the yield stress of the material . When the restraints are removed, these stresses will be partially relieved by the movement, or "distortion", of the base metal. The remaining unrelieved stresses that are internal to the weld (and often still near yield stress values) are known as "residual stresses".

During cooling, if the adjacent base metal is unrestrained, then the increased contraction of the weld will result in significantly increased distortion. At the same time, with this increased movement, tensile stresses will be relieved further and residual stresses reduced.

4.0 Types of Weld Distortion

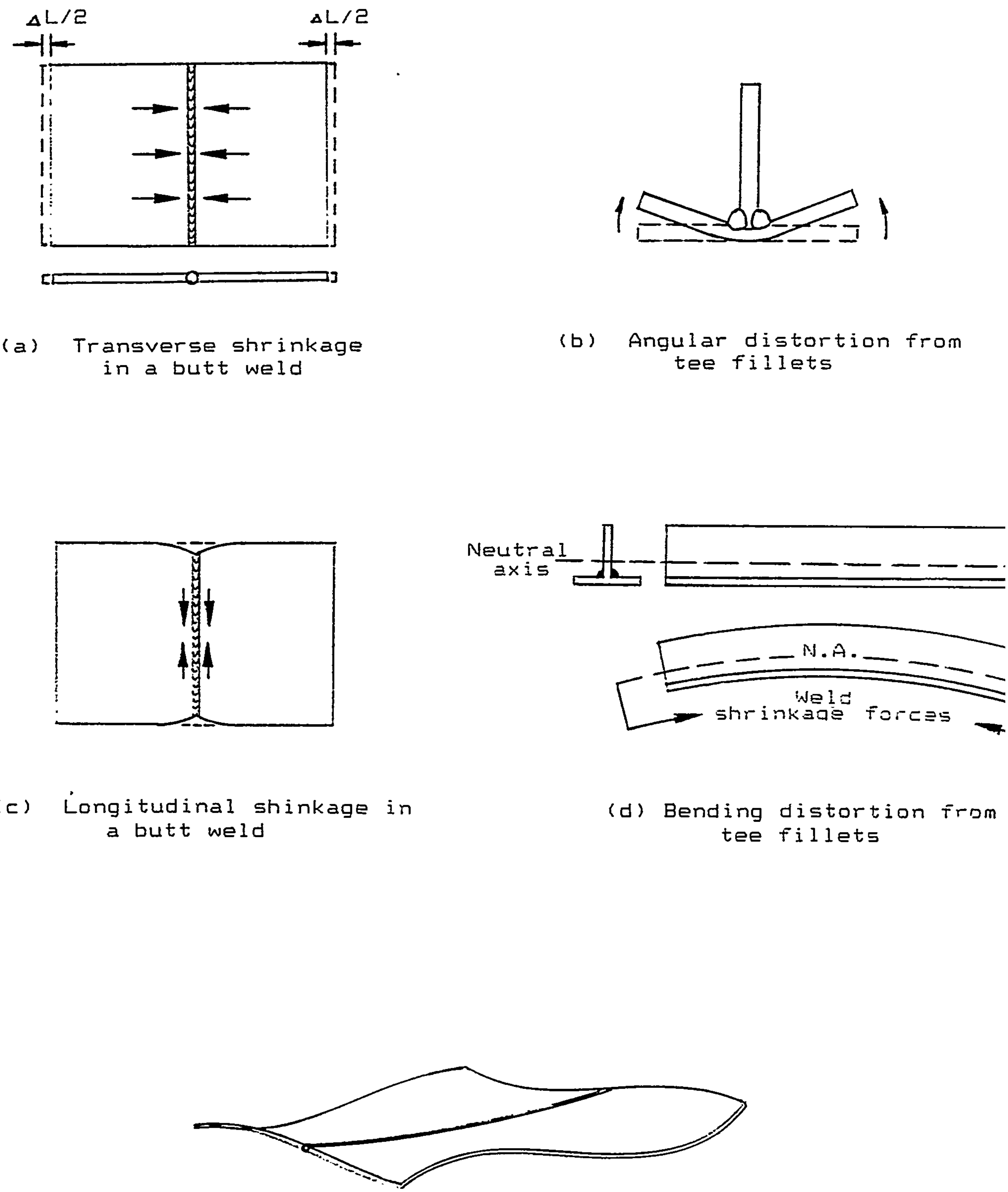
As a weld cools, it contracts in all directions and forces dimensional changes upon the weldment. These dimensional changes may be described as various fundamental types of distortion (ref 1):

4.1 Transverse shrinkage -- occurs perpendicular to the weld line, as illustrated by the butt welding of two plates in Figure 3(a) .

4.2 Angular distortion -- occurs when transverse shrinkage does not occur uniformly throughout the thickness of the piece. For example. as in Figure 3(b), the fillet in a buiit-up tee section does not penetrate the flange completely. The transverse shrinkage forces on the top of the flanqe are resisted by the bottom of the Flange and cause a rotation around the weld,

4.3 Longitudinal shrinkage –– occurs parallel to the weld line, as illustrated by the butt welding of two plates in Figurs 3(c).

4.4 Longitudinal bending (bowing) -- occurs when weld shrinkage occurs at some distance away from the neutral axis of the weldment. As an example, Figure 3(d) shows



(a) Transverse shrinkage in a butt weld

(b) Angular distortion from tee fillets

(c) Longitudinal shinkage in a butt weld

(d) Bending distortion from tee fillets

(e) Buckling distortion from a butt weld in thin plating

Figure 3. Fundamental types of weld distortion

longitudinal bending that occurs in a built-up tee section. As the fillets shrink longitudinally, a bending moment is developed about the neutral axis of the tee, producing a "bowing effect".

4.5 Buckling distortion -- occurs in thinner plating where residual compressive stresses of the weld overcome the resitance of the plate to buckling in areas away from the weld. As the butt weld in Figure 3(e) shrinks longitudinally, the thinner plating away from the weld must conform (since it is not strong enough to resist) to the same length longitudinally and buckles.

5.0 Calculation of Weld Shrinkage and Distortion

Formulas for estimating shrinkage and distortion amounts, provided from a number of references, are identified in Figure 4.

Since weld shrinkage and distortion can vary greatly with the type of welding process, welding speed, degree of restraint, etc., these calculations should be used as estimatss only. For complex weldments, the only practical means for determining the distortion effects is on a trial basis. When accomplishing this, however, it is important that careful control is maintained over the variables (assembly procedure, fitup accuracy, weld sequence, etc.) that affect the distortion. Only in this manner may the results be interpreted correctly and repeatability of the control measures be expected.

6.0 Allowances for Weld Shrinkage

The U.S. Navy provides allowances for weld shrinkage in Mii-Std-l689(SH), "Fabrication, Welding, and Inspection of Ships Sructure", as shown in Figure 5. As stated, these allowances are for "guidance only and will depend on factors such as fixturing, joint restraint, welding process, sequence of weldings heat input and size of welds."

Figure 4. Calculation of Weld Distortion, Carbon and Low Alloy Steels

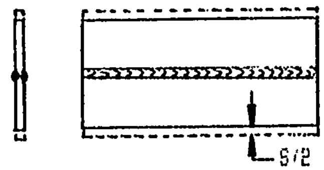
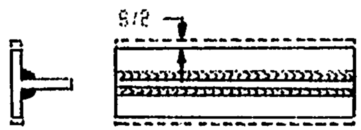
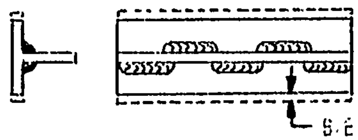
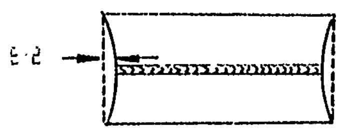
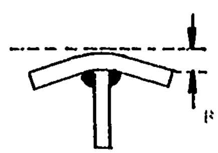
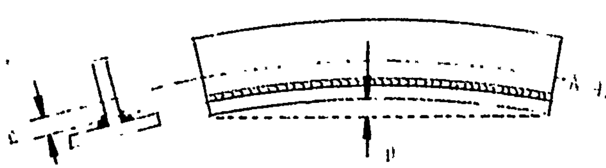
Type of Distortion	Type of Weld		Formula		Reference
Transverse Shrinkage	Butt Weld		$S = (C)\frac{A_w}{t} + 0.05(d)$	S = transverse shrinkage (in) A_w = cross sectional area of weld (in^2) t = thickness of plates (in) d = root opening (in) C = 0.20 for t = 1 inch or greater = 0.18 for 1/4 inch < t < 1 inch	1, 5, 20, 23
	Fillet Weld, Tee Joint with Two Continuous Fillets		$S = 0.04\frac{D_f}{t_b}$	S = transverse shrinkage (in) D_f = fillet leg length (in) t_b = thickness of bottom plate (in)	5
	Fillet Weld, Tee Joint with Intermittent Fillets		$S = 0.04\frac{D_f}{t}\ C$	S = transverse shrinkage (in) D_f = fillet leg length (in) t = thickness of bottom plate (in) C = correcting factor, proportional length of weld to total joint	5
Longitudinal Shrinkage	Butt Welds Fillet Welds		$S = 0.025\frac{A_w}{A_p}$	L = longitudinal shrinkage (inches per inch of weld length) A_w = cross sectional area of weld (in^2) A_p = cross section of plate (in^2) *** accurate only when $A_p < 20A_w$	5, 20
Angular Distortion	Fillet Welds, Tee flange to web		$A = 0.02\frac{(W)(\omega^{1.3})}{t}$	A = angular distortion (in) W = flange width (in) ω = weld size (in) t = flange thickness (in)	25, 26, 27
Longitudinal Bending	[illegible]		$\Delta = [illegible]\frac{(A)(d)\,L^2}{I}$	Δ = longitudinal distortion (in) A = cross sectional area of weld (in^2) I = moment of inertia (in^4) L = length of welded member (in) d = distance from neutral axis to CG of weld (in)	25, 26, 27

Figure 5. Shrinkage Allowances in Mil-Std-1689(SH) (Guidance Only)

I. Butt Welds

Shrinkage Direction	Plate Thickness	Shrinkage Allowance
Transverse	all thicknesses	1/16 to 3/32 inch for all thicknesses
Longitudinal	over 1/2 inch	1/32 inch in 10 feet
	over 3/8 to 1/2 inch inclusive	1/32 to 1/16 inch in 10 feet
	over 1/4 to 3/8 inch inclusive	1/32 to 3/32 inch in 10 feet
	1/4 inch and less	1/16 to 1/8 inch in 10 feet

II. Fillet Welds

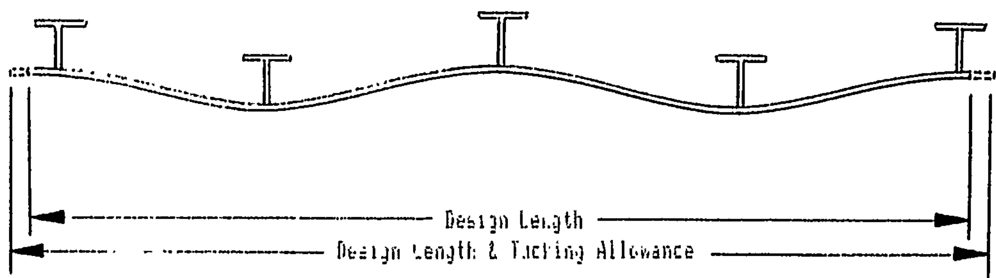


Plate Thickness	Tacking Allowance
over 1/2 inch	No allowance
over 3/8 to 1/2 inch inclusive	1/64 inch per stiffener
over 1/4 to 3/8 inch inclusive	1/32 inch per stiffener
1/4 inch and less	1/16 inch per stiffener

7.0 Structural Fairness Requirements

Structural fairness requirements for U.S. naval surface ships are provided in Mil-Std-1689(SH).

7.1 Unfairness of welded plate:

Figures 6 and 7 provide the unfairness (deviation from molded line) tolerances for steel and aluminum welded plating in the following areas:

(a) Entire shell.
(b) Uppermost strength deck.
(c) Longitudinal strength structures within the midships 3/5 length for displacement type ships, or as specified for other type ships which includes innerbottoln tank and the uppermost strength deck if continuous above machinery spaces.
(d) In transversely framed ships, the permissible unairness for structure noted in (a), (b) and (c) above is reduced by 1 inch.
(e) Bulwarks and exterior superstructure bulkheads.

Figures 8 and 9 provide the unfairness tolerances in steel and aluminum welded plating for the following areas:

(a) Structural bulkheads forming a boundary of a living space (stateroom, office, berthing, messing or lounge area) and passageways contiguous to such spaces.
(b) Decks within the hull and superstructure in way of the above living spaces.
(c) Decks exposed to the weather.
(d) Tanks and main transverse bulkheads.
(e) Innerbottom plate longitudinal.

7.2 Bows in frames, beams and stiffeners:

Tolerances (plus or minus from the designed or molded line) for bows in frames, beams and stiffeners in primary strength structure or structure subject to dynamic

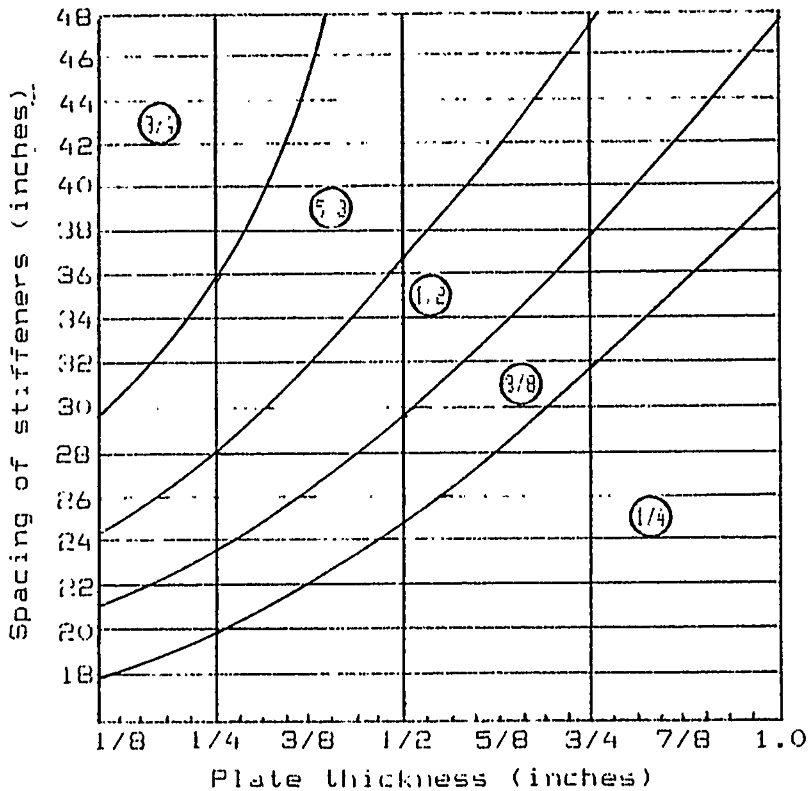


Figure 6. Permissible unfairness for steel welded structures per Mil-Std-1689(SH)

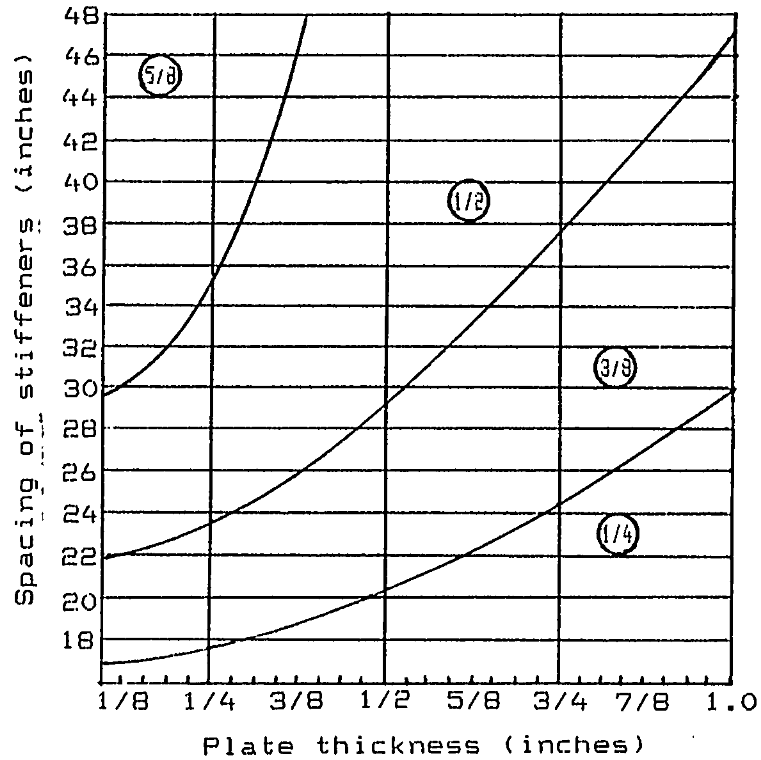


Figure 7. Permissible unfairness for aluminum welded structures per Mil-Std-1689(SH)

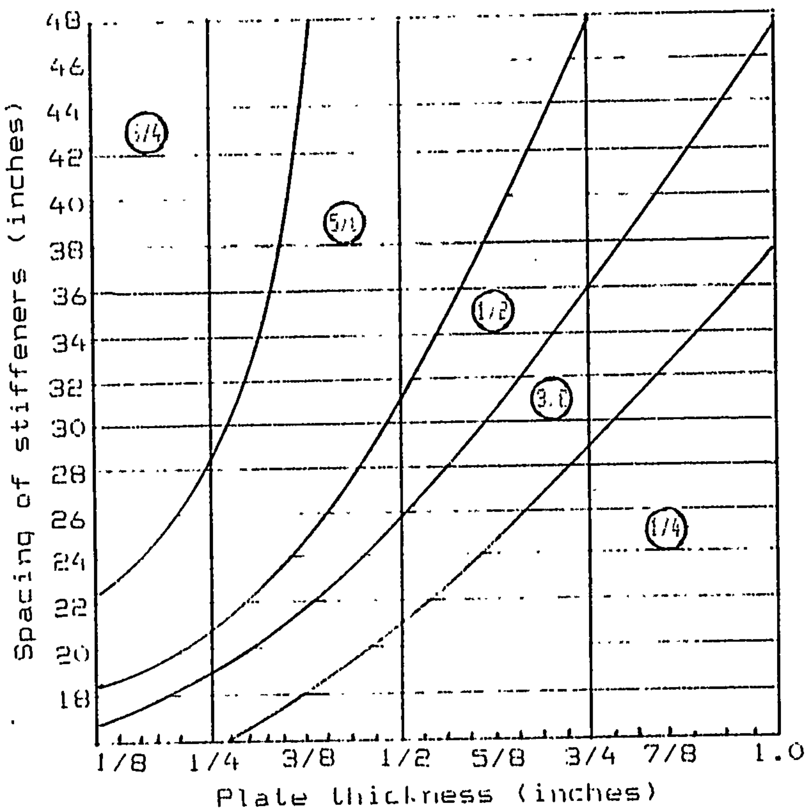


Figure 8. Permissible unfairness for steel welded structures per Mil-Std-1689(SH)

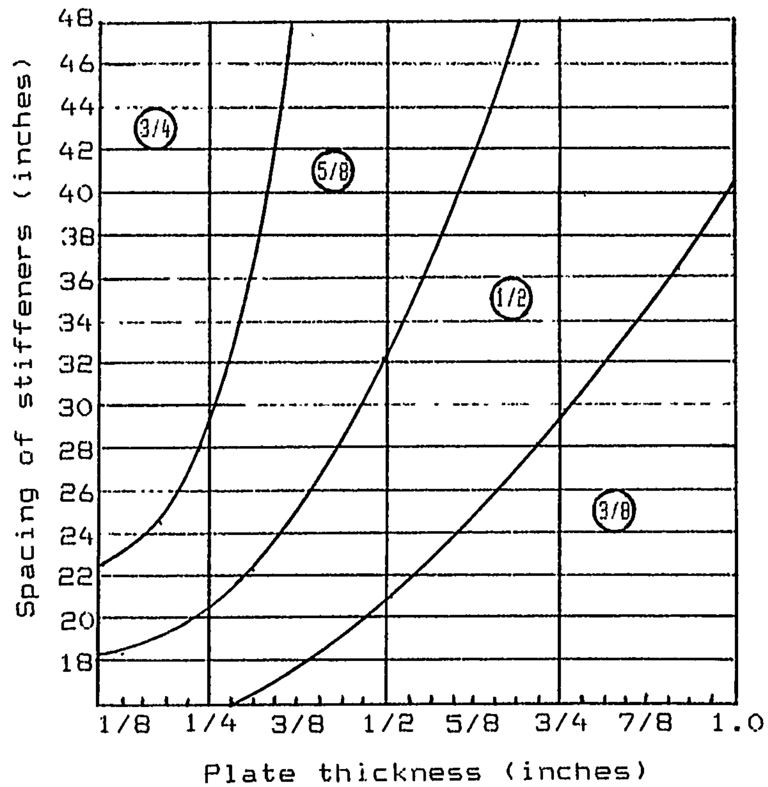


Figure 9. Permissible unfairness for aluminum welded structures per Mil-Std-1689(SH)

loading are established by:

tolerance (inches) = span (feet) / 4 x depth (inches)

where "span" is the distance between the fixed ends at support structure and "depth" is the depth of a stiffening member measured from the underside of the flange. The measurement must be taken from the most distorted position in the web.

7.3 Deviations from the molded form:

Deviations of ships structure from the molded form should not Eexceed :

(a) Plus or minus 1/2 inch from the veritical longitudinal centerplane with an additional plus 1/2 inch tolerance for ships greater than 100 feet in beam.
(b) Plus or minus 1 inch in 100 feet of length.
(c) Plus or minus 1 inch of beam with an additional plus 1 inch tolerance for ships greater than 100 feet in beam.
(d) Between deck heights are to be within plus or minus 3/8 inch. Acclumulated deviation at any deck level shall not exceed plus or minus 1 inch from the molded deck line. An additional accumulated deviation tolance of plus 1/2 inch is permitted for ships with greater than 50 feet from baseline to uppermost continuous deck.

When working to any specification tolerances for a product, it must be kept in mind that the function of the product and not necessarily its cheapest manufacture were the critaria used in their establishment. Thus, the in-process tolerances that are necessary to minimizs construction casts may be much tighter than those required in the final product.

As an example, the 1/2 inch unfairness tolerance allowed for a steel deck (3/8 inch plating with 27 inch stiffener spacing) in Figure 6 could certainly cause installation problems for a machinery foundation or deck drain in that location. Consequenly, the effects of distortion on the next

stage of construction must be considered when establishing in-process tolerances.

8.0 Distortion Control Methods

Extensive literature exists describing methods for reducing distortion. In fact, much of the information necess ary to significantly reduce distortion in shipbuilding currently exists. What is required is a much better understanding and widespread application of these methods in both design and production. In particular, these methods must be thoroughly understood by 1st line supervision so that monitoring of weld sizes, sequence of assembly, choice of fixturing,weld sequenc-ing, etc., are routine considerations in the fabrication of weldments.

A review of these distortion control methods is provided here as a general guidline in the application of distortion control to the innumerable design and construction circumstances that occur in shipbuilding. Summary comments concerning those methods which were tested are also included.

8.1 Distortion Control in Design

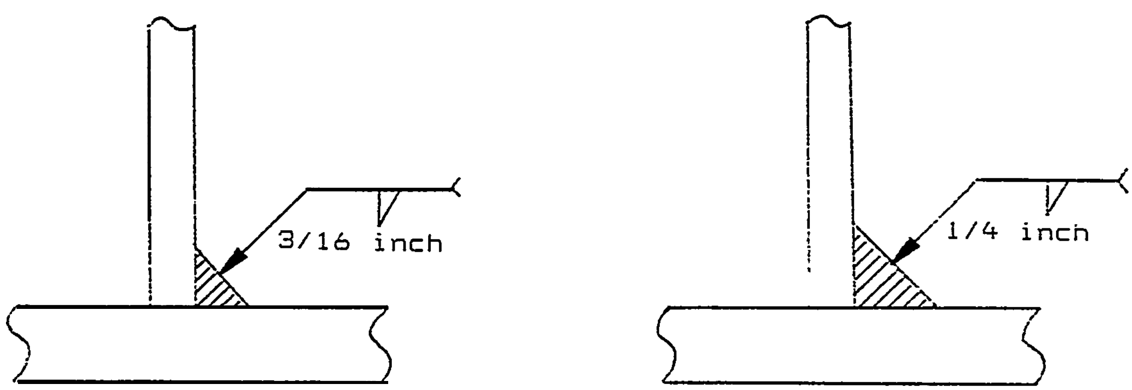
8.1.1 Minimize weld design sizes.

Transverse shrinkage in a butt varies with the cross-sectional area of the weld. Thus, reducing the weld cross-section will reduce shrinkage. For buts in thicker plate this may be accomplished by reducing the bevel angle and decreasing the root gap, using "3" and "U" joints, or using double "V" joints (ref 24).

For fillets, only the smallest leg length necessary to support strength requirements should be used. It must be kept in mind that the cross-sectional area of a fillet varies with the square of the leg length. For example, as in Figure 10, if the leg of a fillet is increased from 2/16" to 1/4", then the cross–sectional area of the weld increases 77 percent.

Cross sectional area
$= (0.188)^2 (0.5) = 0.01767$ in.

Cross sectional area
$= (0.250)^2 (0.5) = 0.03125$ in.



In comparison, the 1/4 inch fillet has a 77 % larger cross sectional area than the 3/16 inch fillet weld.

Figure 10. Effect of small increase in leg length on the cross sectional area of a Fillet weld

8.1.2 Joint location to balance shrinkage forces

Joints should be located to balance shrinkage forces around the neutral axis of a weldment. Figure 11 illustrates how weld joints may be located to produce offsetting bending moments and reduce distortion.

In a butt weld, the use of a double-vee rather than a single-vee joint places equal volumes of weld on each side of the plate, as shown in Figure 12, thereby balancing shrinkage forces around the neutral axis.

8.1.3 Intermittent welding

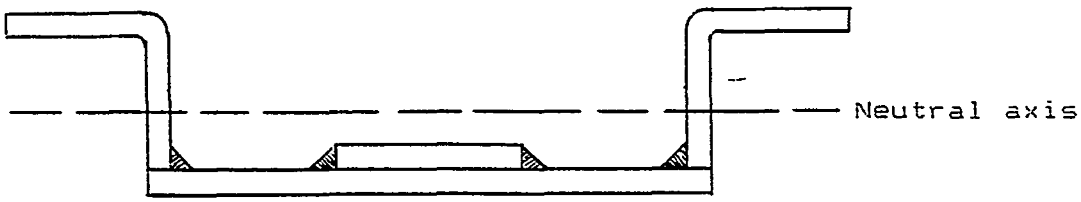
Intermittent welding involves the use of alternating weld segments in a joint with non-welded segments. Where strength requirements permit, intermittent welding can reduce the total weld volume of the joint considerably. Figure 13 shows the chain and staggered intermittent weld types. In accordance with Mil-Std-1689(SH), intermittent welding should not be used on primary ships structure or areas exposed to water or weather.

8.1.4 Material properties

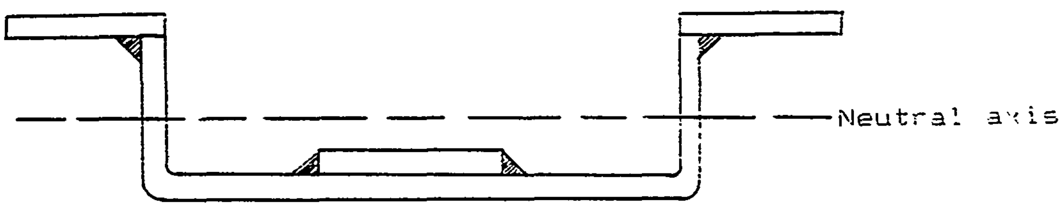
The choice of materials plays an important role in the distortion of the weldment. Physical and mechanical material properties such as the coefficient of thermal expansion, thermal conductivity, modulus of elasticity and yield strength can provide insight into eventual distortion problems in fabrication (ref 22).

The "coefficient of thermal expansion" defines the amount of expansion that a material undergoes for each one degree rise in temperature, and the amount of contraction when temperature decreases. High coefficients of thermal expansion will cause greater contraction during cooling of the weld and heat affected zone, thereby increasing distiortion.

"Thermal conductivity" defines the rate at which a material transfers heat. Low thermal conductivity will cause slower heat transfer from the weld area, a higher thermal gradient

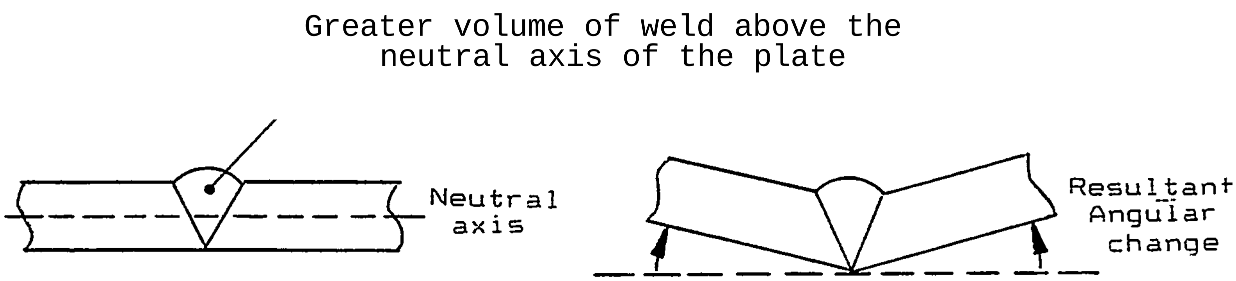


Poor joint location

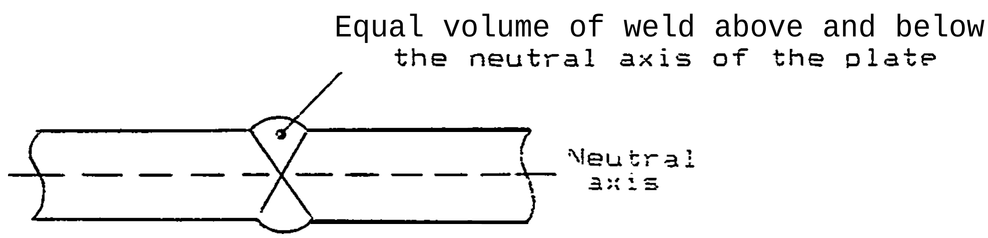


Better joint design, balanced around the neutral axis

Figure 11. Locating weld joints to balance shrinkage forces around the nuetral axis of a weldment

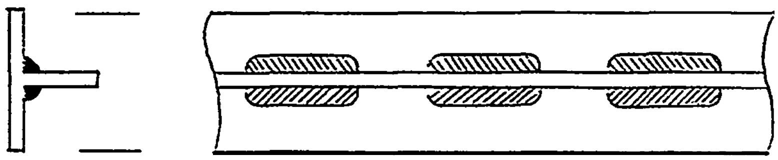


a) Angular distortion in a single vee joint

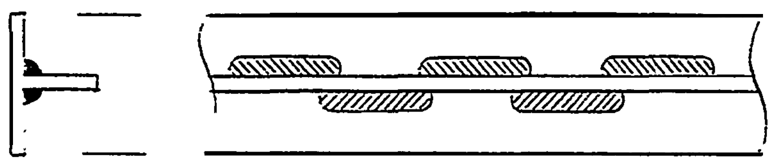


b) Balanced forces in a doubls vee joint

Figure 12. Minimizing angular distortion in a butt weld using a double vee versus a single vee joint



Chain intermittent weld



Stagered intermittent weld

Figure 13. Two types of intermittent welds

and greater distortion.

The "modulus of elasticity" defines the proportional relationship of stress to strain, or stiffness, of a material. A low modulus of elasticity will be less stiff, allowing increased strain (or streching) from weld stresses and increased distortion.

"Yield strength" defines the stress level at which an arbitrary deviation from the proportional stress/strain relationship exists (often at the stress where 0.002 in/in strain occurs) . As a weld and heat affected zone cools and contracts, near yield strength stresses are developed. Consequently, high yield strength materials result in higher stress levels and increased distortion.

8.1.5 Design stiffness

Longitudinal bending is resisted by the moment of inertia of the weldment. Where minimizing distortion is critical, increasing this design characteristic can reduce this distortion.

Buckling distortion is much greater than bending distortion and must be of particular concern with thinner plated structures. Control of plate thickness and the span between supports so as not to exceed critical values can prevent this distortion (ref 5).

8.1.6 Weld shrinkage

The dimensional accuracy of subassemblies routinely affects the accuracy of their fitup. When accuracy of the parts is poor, inaccurate fitup and overwelding is often the result. The incorporation of weld shrinkage values increases the accuracy of parts, thereby reducing poor fitup, overwelding and distortion.

8.2 Distiortion Control in Production

8.2.1 Construction sequence

in planning the constructiton of a complex weldment, the weldment may be broken down into subassemblies so that each subassembly may be welded about its own neutral axis.

In this manner, each individual subassembly may be fabricated with minimum bending distortion. In addition, what distortion does occur may be more easily removed in the smaller, more flexible subassemblies than in the completed weldment.

8.2.2 Fitup accuracy

Fitup accuracy is critical to minimizing weld distortion. Improper fitup will cause overwelding and increased distortion. Where a minimum/maximum root gap is specified in accordance with the joint design to insure proper penetration, fitup should be to the minimum root gap requirement as much as possible.

8.2.3 Presetting

Presetting of parts can be used to offset anticipated weld distortion as shown in Figure 14. Though not an exact method, presetting becomes increasingly effective through experience, as the ability to predict distortion direction and extent improves.

Presetting can be used to offset the bending distortion that occurs in larger, as well as smaller, weldments. As a part of this report, presetting of 56 by 80 ft innerbottom units (combined with the use of weld sequencing and restraint) was investigated as a means of accommodating the bending distortion incurred on previous hulls. Results proved favorable and will be discussed later in this report.

8.2.4 Prehending

Prehending is used to offset anticipated weld distortion in the same manner as presetting. Figure 15 shows a prebent flange being used to offset the anticipated angular distortion in a tee joint.

8.2.5 Prestraining

Prestraining is accomplished by elastically stretching a part to offset weld shrinkage amounts. As shown in Figure 16, bending of the plate will stretch its surface to offset the transverse shrinkage of the fillet welds.

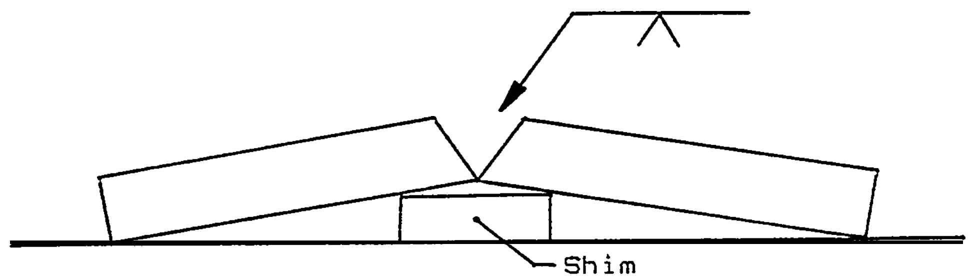


Figure 14. Presetting of plates to offset the angular distortion of a butt weld

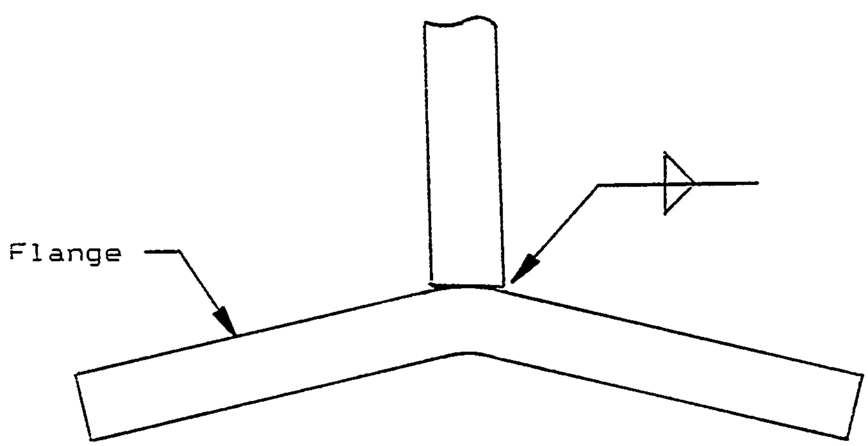


Figure 15. Prehending of plate to offset the angular distortion of fillet welds

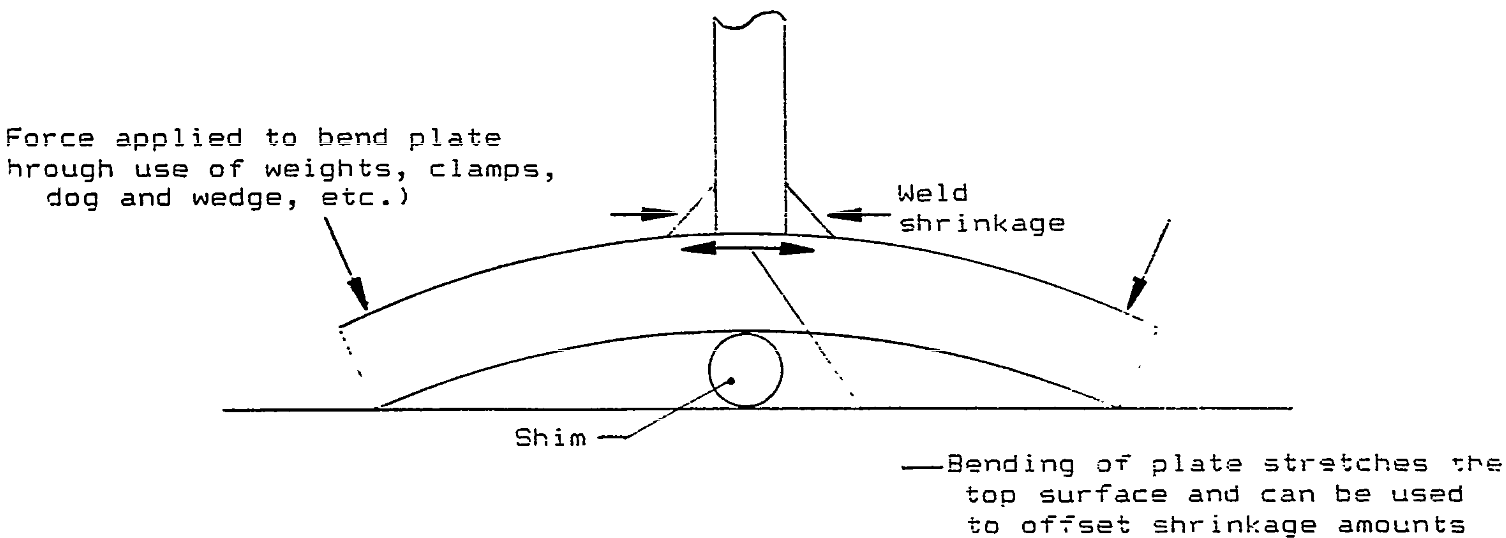


Figure 16. Prestraining (stretching) of plate to offset the angular distortion in a fillet weld

8.2. 6 Restraint

Restraint imposed on a weld can significantly reduce shrinkage amounts. Unlike some misconceptions, when the restraint (by clamps, turnbuckles, dogs, strongbacks, etc.) is removed, the weldment will not spring back to the same distorted condition that would have occured if restraint had not been used during welding. This distortion is elastic and much smaller in comparison to the shrinkage amounts that would have occured without restraint.

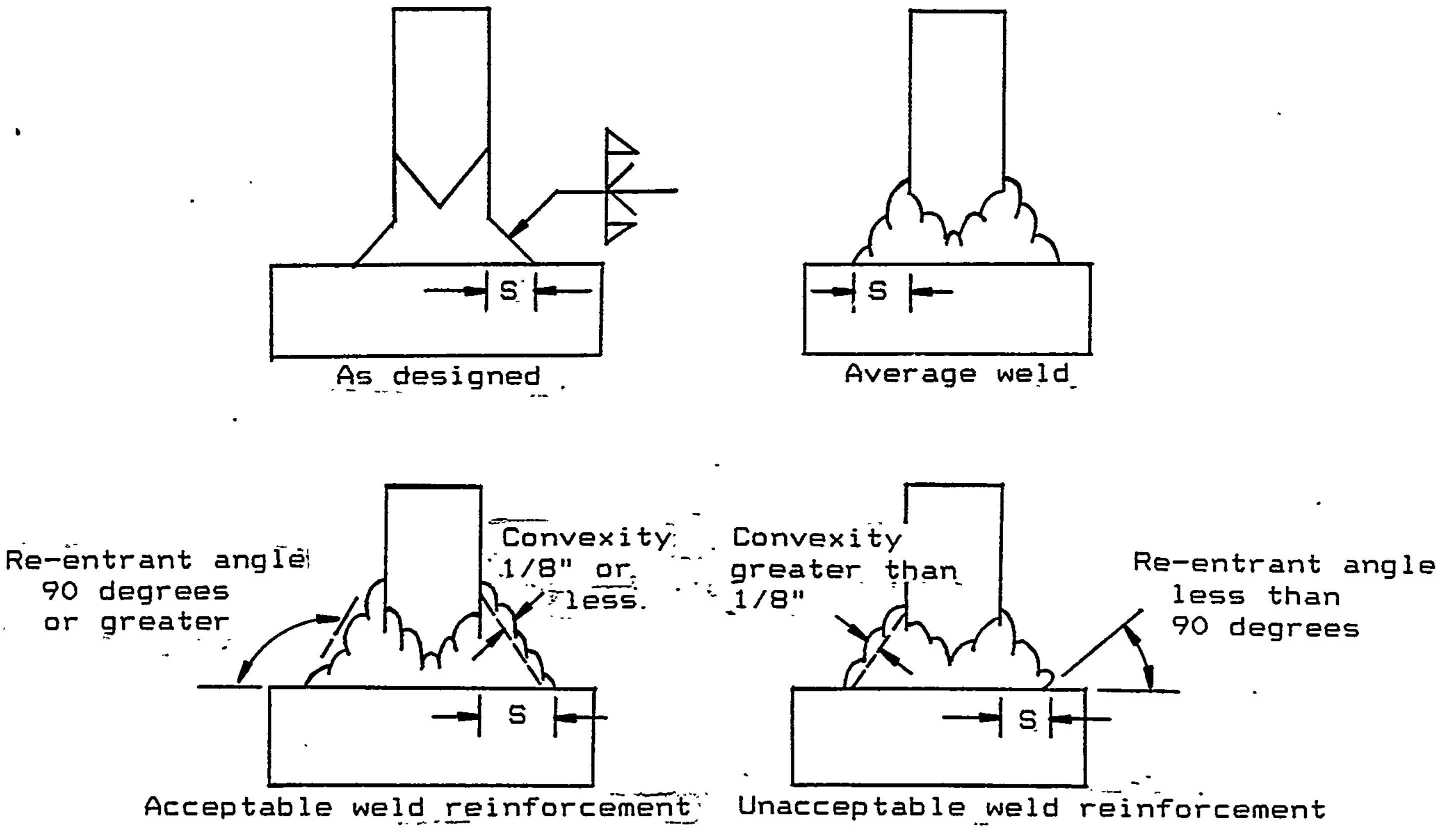
Although distortion will be reduced, restraint increases residual stresses and can lead to weld cracking. Proper welding sequence, and preheating with thicker plating, can be used to minimize these consequences.

8.2.7 Overwelding

Welds should not exceed the design size requirements. Fillets should maintain the design leg lengths. Fillet and butt weld contours should be flat or only slightly convex, minimzing the excess weld reinforcement that adds to shrinkage (ref 26).

Weld size specifications for navy surface ships are defined in Mil-Std-1689(Si-i). Fillet sizes in excess of design are al lowed as long as the contour is in accordance with Figure 17. As shown in this figure, convexity of the fillet is limitedto 1/8" or less. Except for butt welds on the hull outer surface where a to 1/16" reinforcement is specified for hydrod\dynamic purposes. no maximum limit is placed on butt weld reinforcement.

Fillant weld sizes sampled at ingalls Shipbuilding to detetrmine the extent cf overwelding provided interesting results and demonstrated the usetfullness of a rout sampling effort. Fillet welds were measured at two separate construction stages: installation of stiffeners



1. S= Required fillet reinforcement.
2. Fillet reinforcment size in excess of that required by plan is acceptable provided the contour is in acccardance with these figures.
3 Although the fillet contour show in this figure is for groove tee welds, the same requirements apply for fillnt welds.
4. Fillet weld reinforcement size shall not vary below the minimum specified.

Figure 17. CONTOUR REQUIRMENTS FOR FILLET REINFORCED TEE AND FILLET WELDS PER MIL-STD-1689(SH)

to panels, and installation of bulkheads to panels. On each panel, 10 sample measurements were taken for each of the various designed fillet sizes required. The percent overwelding by volume was calculated for each fillet size and then Compared to the other panels measured in the same construction stage to determine the "normal" accuracy of weld sizes. Results showed that:

- Underwelding was found very infrequently and could be attributed to welder training in this regard.

- Overwelding was minimal on the larger fillet sizes, 1/4" and greater. Overwelding was increased on the smaller welds that are often much more difficult to obtain. The smaller 3/16" fillets produced relatively high amounts of 55.8 and 54.3 percent overwelding in the initial sampling effort.

- During the sampling effort, a significant reduction in overwelding was seen for the 3/16" welds in both construction stages. As shown in Figure 18, nearly identical reductions of approximately 40% were observed in each of the stages.

  This improvement can be primarily attributed to the priority on accuracy set by welding supervision. Specific actions included the establishment of routine sampling of weld sizes, training classes for all supervisors and workleadermen, the posting of example weld sizes at the work site, the use of on–the–job instructors in the field, and the development and distribution of pocket-sized guides for fitting and welding.

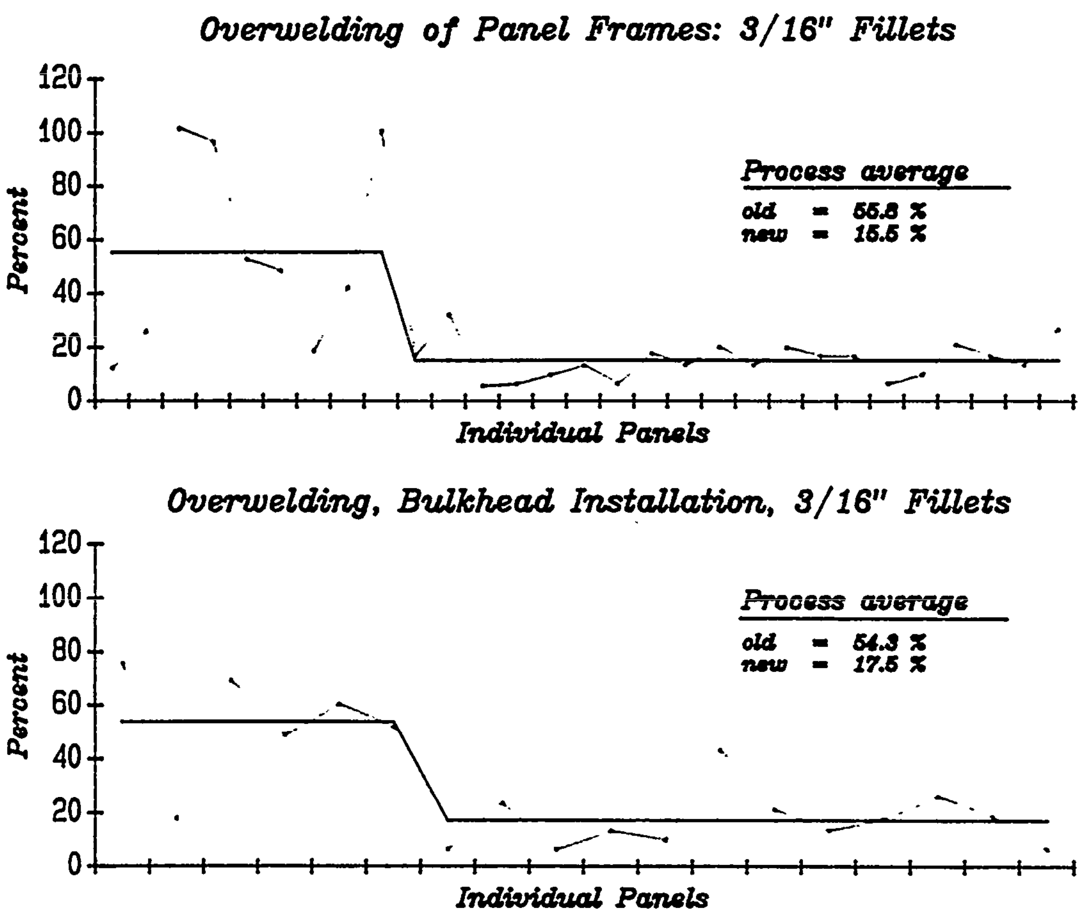


Figure 18. Approximate 40 % reduction in overwelding of 3/16 inch fillet welds measured through random sampling in two separate construction stages

8.2.8 Weld sequencing

Sequencing of welds may be approached in three respects: (1) sequencing of weld segments within a pass, (2) sequencing of passes within a joint, and (3) sequencing of joints within a weldment.

The "backstep" sequence is a commonly used distortion control method that involves the sequencing of individual segments within a pass. In this technique, a pass is completed by stepping through it using short individual segments that are opposite in direction to the general progress of the weld, as shown in Figur 19. By welding towards a previously welded location through each segment, restraint is added to the segment which minimizes its distortion. Backstep welding is most economically used with manual and semi-automatic welding processes. Figure 20 is an example of backstep welding used at Ingalls Shipbuilding on the LHD contract bow unit.

The effectiveness of backstep welding in reducing angular distortion as compared to a wandering backstsp sequence and a continuous weld was investigated as a part of this study. Results indicated that backstep welding significantly reduces distortion. A more detailed explanation will be provided later in this report.

In a multipass weld, the sequencing of Passes from one side of the neutral axis of a weldment to the other side can be used to balance shrinkage forces. Figure 21 illustrates how the alternating of passes from one side of a double-vee butt joint to the other side can be used to minimize angular distortion.

Sequencing of joints within a weldment is accomclished so that shrinkage forces in each joint or group of joints are similarly offsetting. Figure 22 snows a typical weld sequence for miscellaneous foundations.

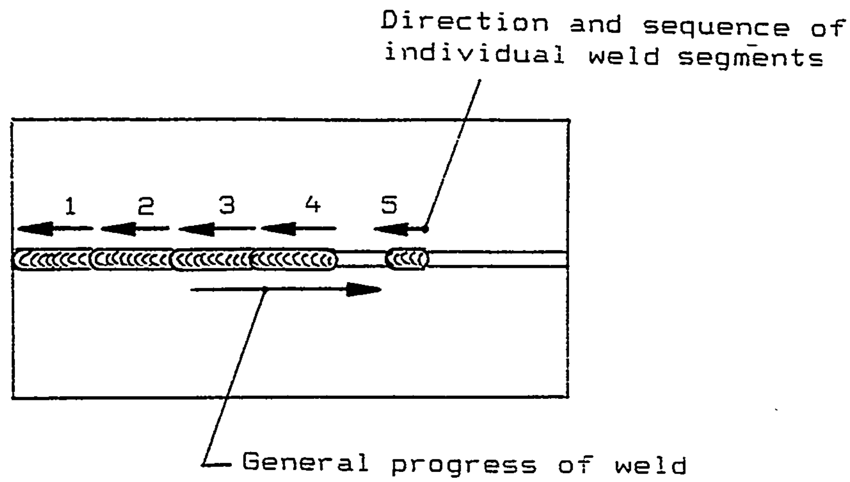


Figure 19. Backstep weld sequence

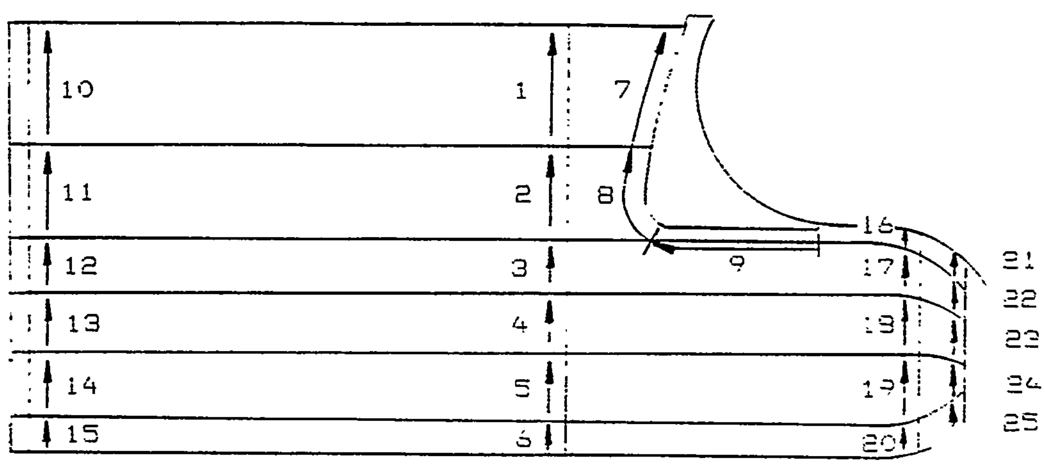


Figure 20. Backstep sequence used at Ingalls Shipbuilding on the vertical welds of an LHD contract bow unit

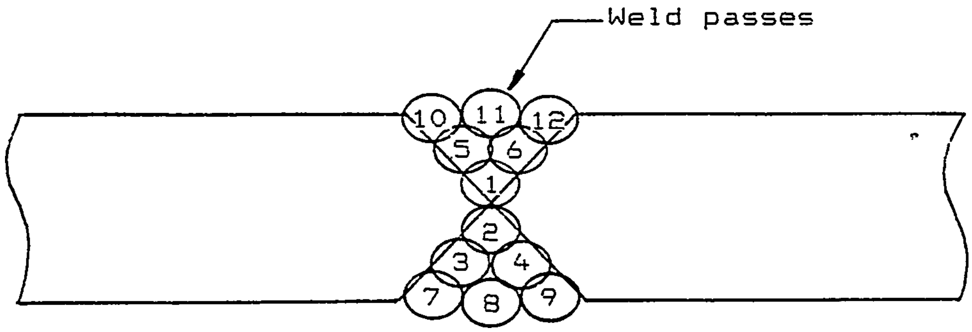


Figure 21. Alternating of passes to each side of a multi-pass butt weld to minimize angular distortion

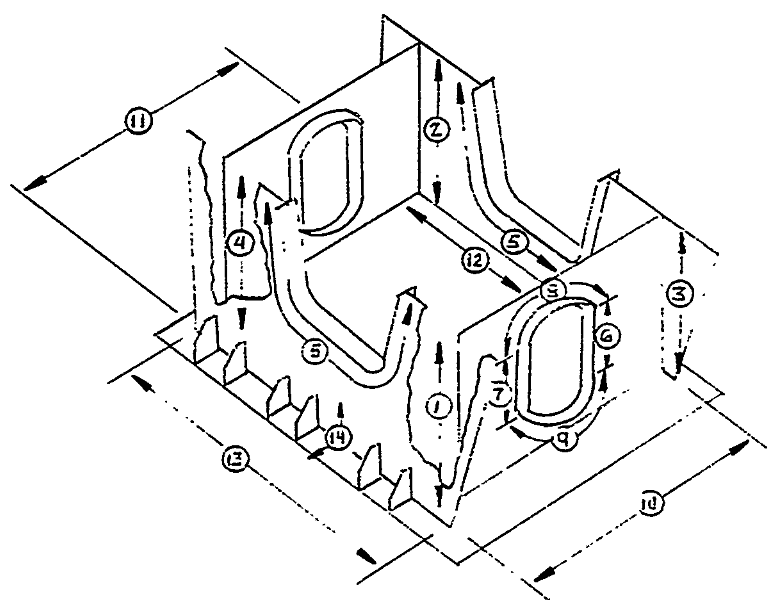


Figure 22. Sequencing of joints for a typical miscellaneous foundation

8.2.9 Minimizing heat input

Heat input may be reduced using semi-automatic or fully automatic processes which allow increased welding speeds over manual welding. The effect of the higher welding speeds is to reduce the range of the heated base metal outside the weld that contributes to shrinkage (ref 26).

If possible, weldments should be positioned so that welding can be accomplished downhand. Downhand welding allows for increased welding speeds versus vertical or overhead positions. A variety of weldment positioners are available that may be used to maximize downhand welding.

On multipass welds, transverse shrinkage may be reduced by minimizing the number of passes as shown in Figure 23. Larger electrodes may be used to reduce transverse shrinkage if they are also used on the first weld pass (ref 5).

8.2.10 Peening

Peening involves the use of mechanical force on the weld that induces plastic flow and the reduction,of shrinkage stresses. Peening is generaliy accomplished using a pneumatic chisel with a blunt round tool. Peening should not be used on the first pass due to the possibility of causing cracking, or on the last pass that may produce a work-hardening effect and/or interfere with weld inspection efforts (ref 29).

8.2.11 Preheating

Preheating is commonly used to reduce the cooling rate of welds to prevent hardening and cracking, particularly with high carbon steels. preheating temperatures range from 60 F in cold weather situations to as high as 1200 F for cast iron. Preheating is applied in a number of wavs including by furnace, torch heating, electrical strip heaters and induction heating. Figure 22 shows strip heaters being used to preheat Hy-BO side shell joints and and a main engine foundation. Temperature control is usually maintaned using special, crayons or pellets That melt at a predefine temperature. Portable pyrometers or thermocouples may also be used for ,measuring the prehsat temperature.

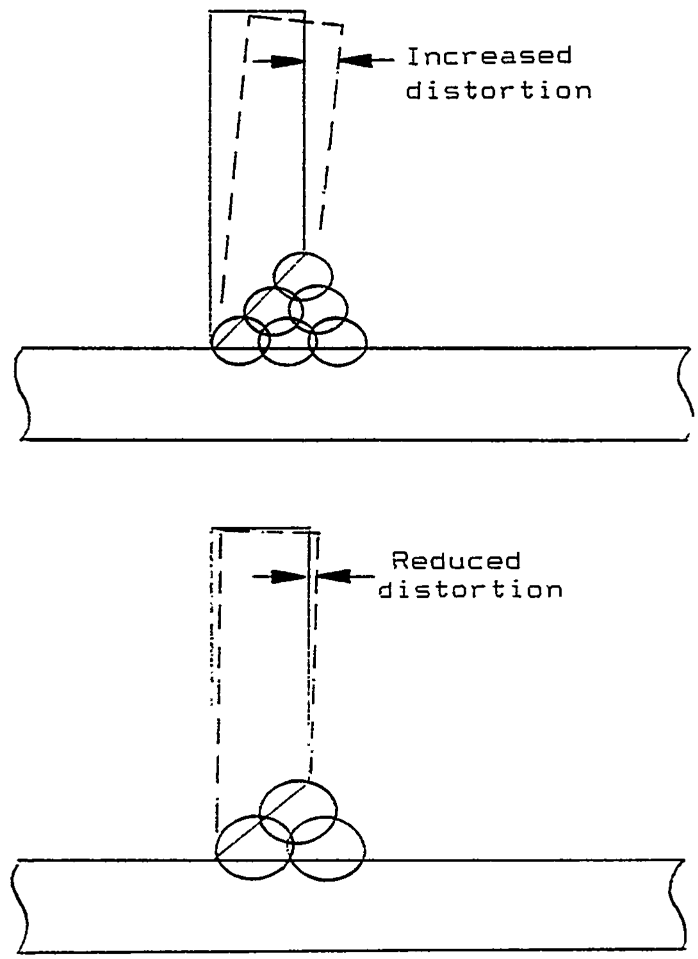


Figure 23. Reducing distortion by minimizing the number of weld passes in a joint

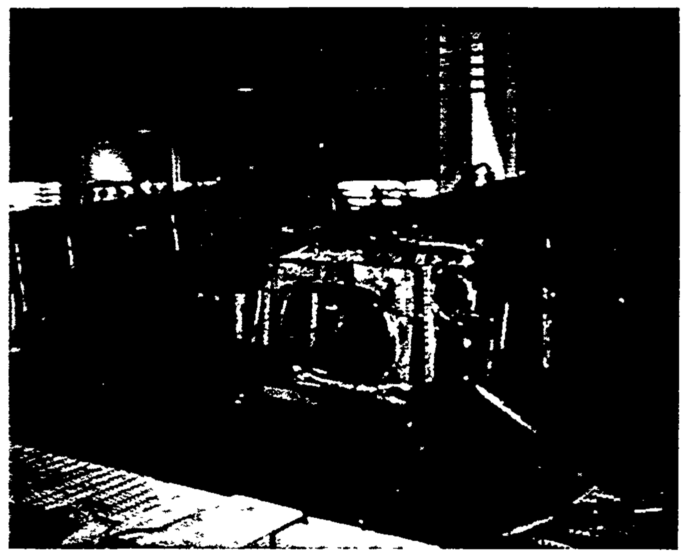


Figure 24. Strip heater being used to preheat HY-80 side shell joints and a main engine foundation

Preheating is primarily used as a means of obtaining proper weld quality. The use of preheating strictly as a means of reducing weld distortion is not nearly as common. The effect of a reduced cooling rate an distortion, as produced through preheating, is not yet well established. Proper preheating temperatures and method of application to minimize weld distortion are similarly undefined.

As a part of this report, the effect of preheating in reducing the distortion of steel panel butts was investigated. Two torches were attached to the SAW gantry and used to preheat the butts to 230 to 260 F. Distortion measurements of preheated and non-preheated butts both interior to the panels and along the edges were compared. Results did not show an improvement in distortion through the use of preheating. A more detailed explanation will be provided later in the report.

8.2.12 Postheating.

Postheating of heavy weldments is commonly used to relieve residual stresses. For most carbon steels, stress relief is accomplished by holding the weldment at a temperature of 1100 F to 1200 F for a period of 1 hour for each inch of its maximum thickness (ref26). Heating and cooling is accomplished slowly, at rates not to exceed 400 F per hour and often less dependent on the ratio of thicker to thinner members. In this manner, disproportionate heating, which could cause increased instead of reduced residual strssses, is avoided.

Postheat stress relief will not correct distortion in a weldment. However, it may be used as an effective means of preventing distortion in weldments that require machining. Tensile and compressive residual stresses are balanced within a weldment. In heavy or highly restrained weldments, these stresses may be at the yield stress of of the material . When material is removed by machining , these stresses become unbalanced and produce distortion. Removal of these stresses by postheat treatment prevents this distortion.

In some cases, duplicate weldments are clamped back to back, welded, and then stress relieved while still clamped together (ref 2). The residual stresses that may have caused distortion are removed so that the weldments remain straight when unclamped.

8.2.13 Vibratory stress relief

To date, vibratory stress relief of weldments has produced mixed reviews. Although seemingly substantiated through numerous successful applications within industry (refs 7-12, 29-34), experimental data has provided inconsistent and often contradictory results (refs 13–15, 35,37). Consequently, vibratory stress relief is not yet allowed as a substitute for thermal stress relief in "code work"

Stress relief is accomplished through mechanical vibration of the weldment. Although not fully understood, this this vibration is thought to induce stresses that combine with the internal residual stresses of the component to exceed the material yield strength and cause strass redistribution through plastic flow (ref 36).

Vibratory stress relief offers significant advantages over thermal stress relief methods. These include the portability of the machines, low operating costs, speed of operation, ability to relieve large weldments by moving the vibrator to various locations on the weldment, and no heat side effects such as scaling, reduction in material strength, or distortion.

Additionally, vibration may be applied during welding. because the amplitude of vibrstion is low, interference with welding operations is not a Problem. Claims of reduced weld cracking and distortion are not yet established by exprimental results.

As a part of this report, the effects on distortion 0f resonant vibration during welding were investigated. To test these effects, mild steel test plates were butt welded with and without vibration at rssonance. Angular distortion measurements were compared. Results showed a definite but

small reduction in angular distortion in the vibrated samples. A more thorough explanation will be provided later in this report.

8.3 Distortion correction.

8.3.1 Flame straightening

Flame straightening is a commonly used method in shipbuilding for correcting distortion. Using an oxy-acetylene torch, heat is applied to the distorted area to raise its temperature to approximately 1100 to 1200 F after which a water quench is applied. Shrinkage is induced which provides the straightening effect.

The means by which flame straightening induces shrinkage is identical to that which produces weld shrinkage. When a localized spot is heated to a high temperature, it attempts to expand but is prevented from doing so by the colder metal adjacent to it. The heated metal expands vertically and is "upset". As it cools, the metal contracts uniformly. Because the upset that occured from heating is not equally reversible upon cooling, then a net e.hrinkage is the result.

Flame straightening is normally applied in patterns that purposely control the direction of shrinkage. These may be described as combinations of three basic patterns that each produce different shrinkage effects: spot heat. line heat and vee-heat patterns, as shown in Figure 25.

Spot heating produces shrinkage effects uniformly in all directions and is often used on largely distorted plating interior to stiffening memebers. as shown in Figure 26. Line heating produces shrinkage effects Primarily transverse to the line. Figure 27 shows linen heats being used on bulkhead plating on the opposite side from stiffeners. vee-heating produces uneven shrinkage, more at the base of the triangle and less near the apex, so that an angular change in the heated area results. Figure 28 shows vee-heats used to correct the bending distortion of a tee.

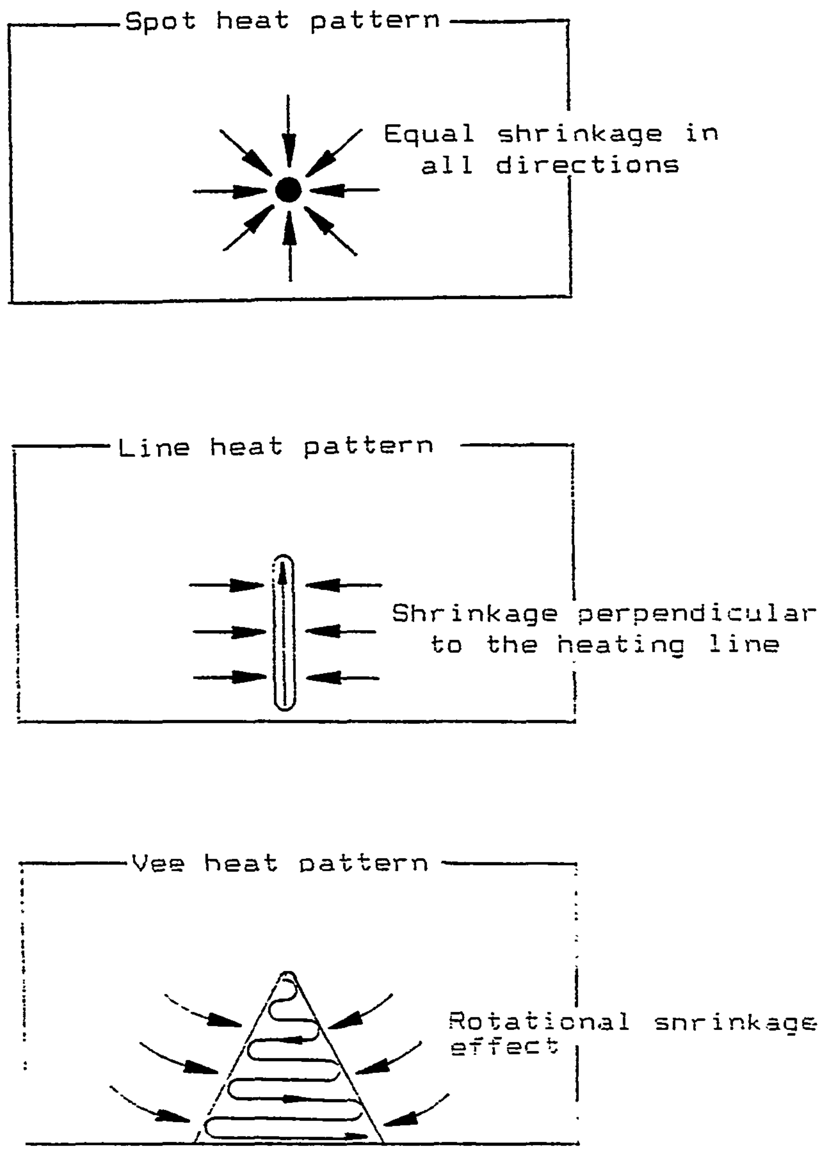


Figure 25. Spot, line, and vee heat patterns used in flame straightening

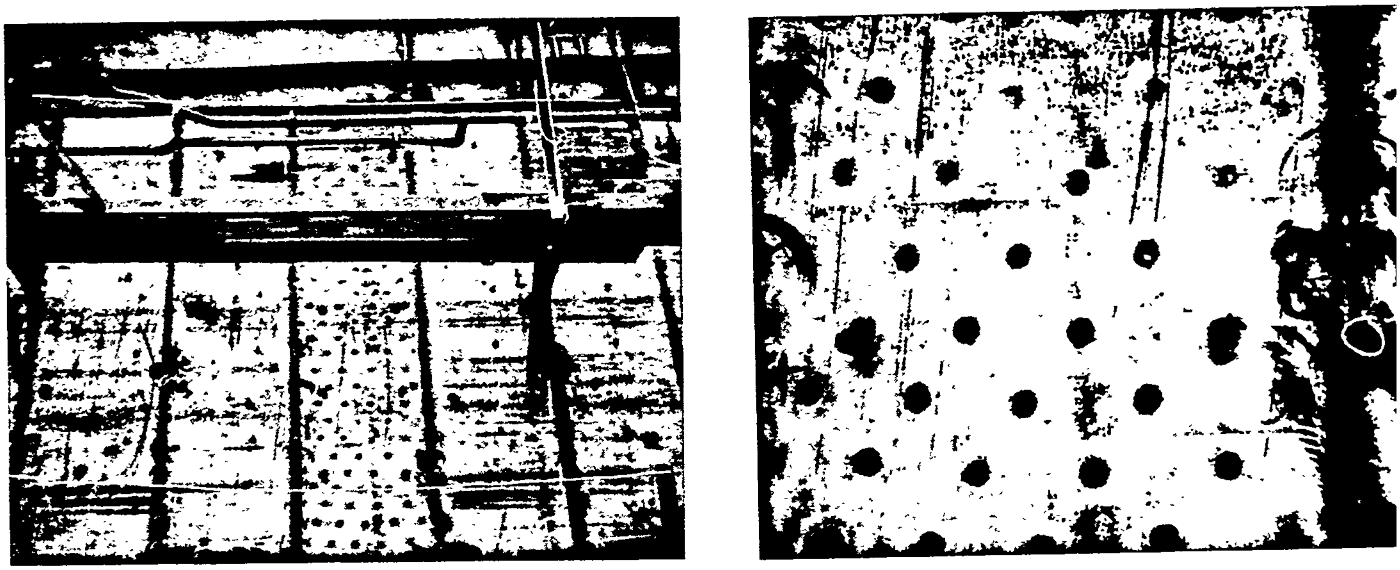


Figure 26. Spot heat pattern used on the plating of a thinner bulkhead, interior to stiffening members

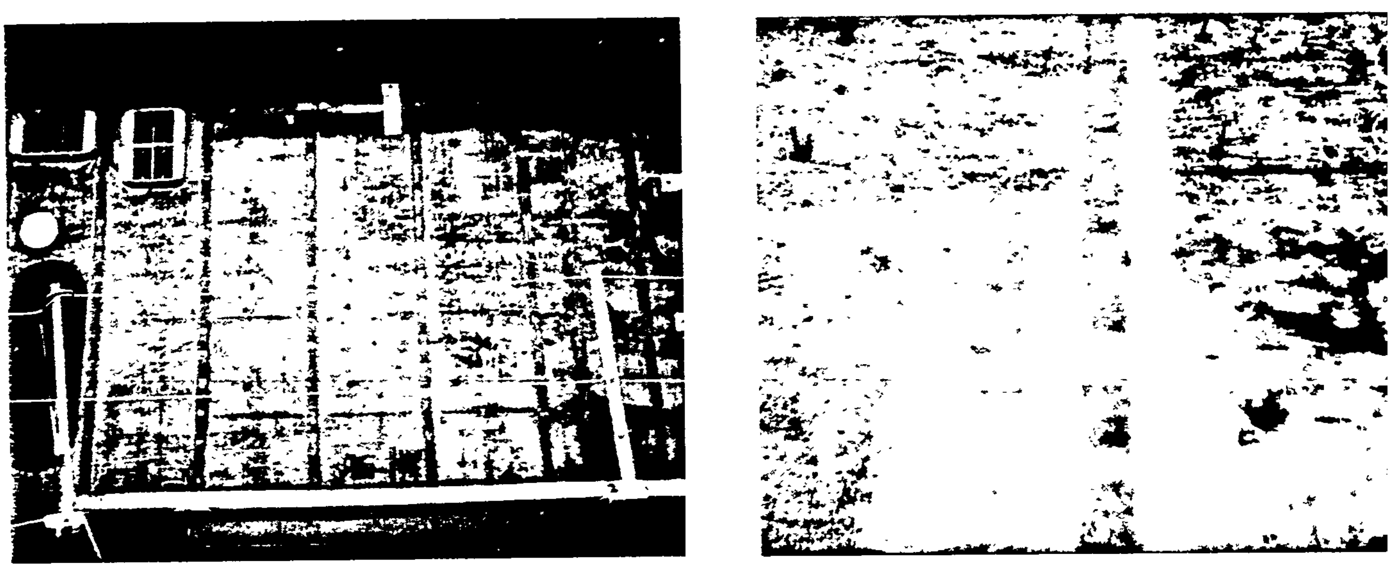


Figure 27. Line heat pattern used on the "smooth" side of bulkhead plat directly opposite and along the length of stiffening members

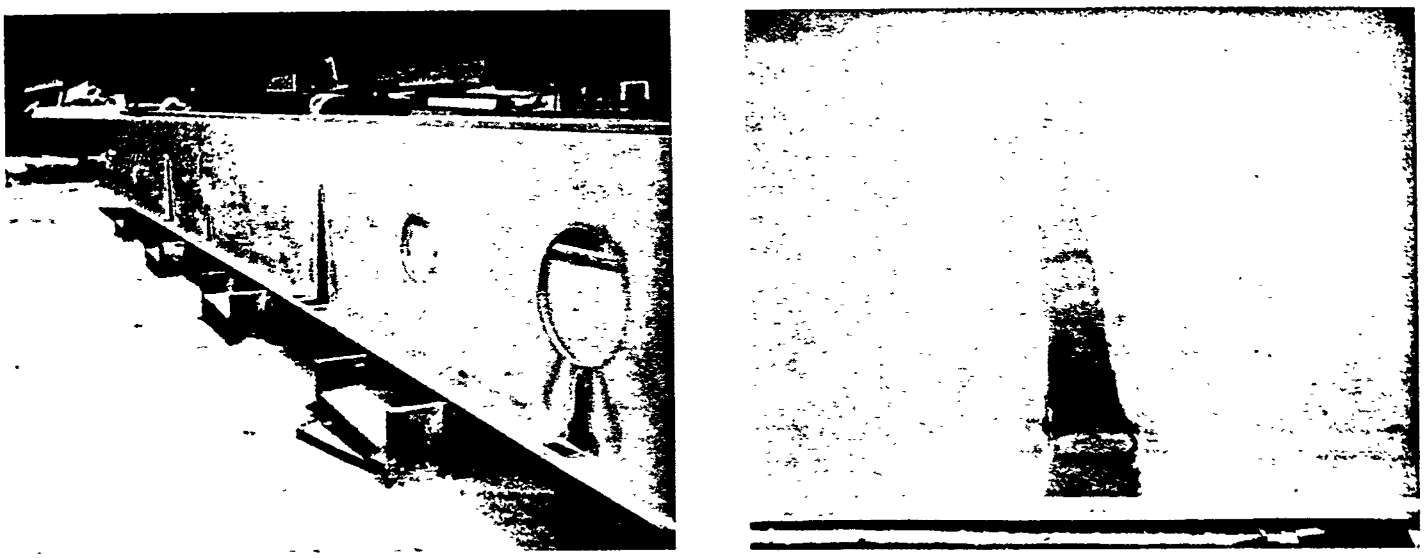


Figure 28. Vee heat pattern used to correct bending distortion in tees caused by flange striping and hole cutting operations

8.3.2 Mechanical correction

Distortion may be corrected mechanically using a press, hydraulic jacks, or even strongbacks and a wedge. In some situations, it may be useful to apply heat in conjunction with these methods to reduce the amount of force required.

8.3.3 Induction straightening

Induction straightening of distortion is much more common outside of the U.S. It accomplishes distortion correction in the same manner as flame straightening: ie., through heating and shrinkage of plating. In this case, however, heat is generated through an induction process.

In this process, an induction unit is used to create a an constantly expanding and collapsing magnetic field that creates eddy currents in the plating. From these currents, heat is generated. Control over the magnetic field strength and/or timing provides control over the amount of heat produced.

As part of this report, the use of induction straightening on the thinner plating increasingly associated with U.S. naval construction was investigated. Two decks of 0.188" through 0.313" high strength (HTS) and high strength low alloy (HSLA) steel were straightened using an induction system. Results showed that nearly all distortion between stiffeners was removed on plate thicknesses 0.25" and above, with a much reduced effect on the 0.188" plating. A more detailed explanation is provided later in this report.

Methods Tested

9.0 Resonant Vibration During Welding

Vibratory stress relief is a technique for stress relieving weldments using mechanical vibration. There is widespread disagreement among those who have evaluated this process. Many within industry use the process routinely and subjectively establish its merit through the "savings" they have achieved (refs 7-12, 30-35). For example,

- A fabrication/machining company in Cassopolis, MI., is reported to have saved 65 percent in stress relief costs of machine tool bases and other large weldments (ref 10). Stress relief time has been reduced 98 percent Improved dimensional stability has allowed achieving 0.002 inch flatness with +/- 0.010 inch tolerance while working 12 x 19 foot 1018 or 1020 hot rolled plates.

- A machining company in Rockford, IL., is reported to have reduced the number of grindings required to meet specifications on a 12x8x75 inch hardened bedplates from 14 down to only 6 grindings (ref 8).

- A northeastern university's machine shop is reported to have used vibratory stress relief on a number of projects (ref 11). In a particualr one, a 24 foot long temperature wind tunnel was fabricated as twelve 3/4" thick stainless steel chambers that bolted together. application during welding of these chambers almost "totally eliminated warpage" and allowed maintaining tolerances of 0.032".

Experimental results have been inconsistent (in some cases within the same experiment) . For exalmple.

- Researchers from Battelle-Columbus useg 1/2" thick 1020 steel place to Form 12" diameter rings (ref 37). The butt between edges was GMA welded. Three rings *were* vibrated during welding, three after welding, and three had no vibration. Outside diameters were then machined and measured for nut-of-roundness. Both vibrated samples snowed better roundness than the non-vibrated rings. However, additional testing in the same manner with a second set of rings produced contradictory results.

In another test, tees made from AISI 1020 steel plate were GMG fillet welded. Tees were then machined on the web and bottom of the flange and measured for surface flatness. Results showed that tees vibrated during welding distorted significantly less than non-vibrated tees, or tees vibrated after welding.

O Researchers in New Zealand welded mild steel tees and measured residual stress levels before and after vibrational treatment (ref 14). Results indicated that the stress levels generated by the vibration were too low to cause a change in residual stress levels. No significant difference in residual stress levels was measursd.

O Researchers monitored the vibrational treatment of a variety of industrial weldments in the Soviet Union (ref 13). During treatment of each weldment, a reduction in current requirements for the vibrator (ranging From 18% to 30%) were noted that supported the conclusion that residual stresses were being reduced. In this theory. as residual stresses are reduced, the weldment becomes more flexible and less power is needed to drive the vibrator.

Additional observations concerning work accuracies and level Of effort supported this concision. Griinding and lapping efforts required on 2.5 ton valve seats were reportedly reduced by over half when using vibrational treatment . Machining accuracy of 1.2 tom bimettalic thrust bearings reportedly increased from 0.6 to 0.3 mm. The resistance to weld cracking in cast components 07 two 100 cubic meter excavator buckets reportedly increased 1.5 times.

o In some oF the most current research on this topic, interim results released in January l99O from stuidies being Conducted for the U.S. Department of Energy Suggest that vibratory stress relief, specificaily, the Meta-is;. system produced by Bonal Technologies, Detroit, MI, cause changes that are "similar to those that arise due to thermal stress relief" (ref 15). However, these results are still inconclusive. It is not yet known whether the changes observed were the result of the stress relief treatment, the interpass tempering effect associated with the multipass weldments tested, or a combination Of both.

This testing was accomplished on flux core welded A36 plates. Tests included tension and impact tests, and analysis of grain structure through both microhardness testing and comparison under a microscope. In addition, subjective observations showed a difference when welding during vibration that included better weld flow, less grinding between passes, and slightly less filler material to complete the weld. Further testing is to be accomplished using AISI 4140 material.

9.1 Theory of Stress Relief Process

Theories explaining exactly how vibration reduces residual stress levels vary. In fact, even within vibratory stress relief industry, there is disagreement whether vibration at resonant or subresonant frequencies will provide the best stress relief.

It is commonly understood that nonuniform coolinq of welds and adjacent base metal producs residual stress patterns as shown in Figure 29. One frequently used explanation for vibratory stress relief proposes that the mechanicaliy induced stresses are additive to the residual stresses in the weldment. In areas of high residual stress, these combined stress levels exceed the yield strength of the material causing plastic flow and redistribution of strssses as shown in Figure 30. From this viewpoint. relatively large stresses such as those produced at the resonant frequency must be induced by the vibration so that the yield strength of the material is exceeded, if only momentarily (ref 36).

Another explanation proposes that the vibration produces an increased activity of atoms in the metal causing them to move from higher to lower energy sites, thus reducing residual stresses. From this viewpoint, it is suggested that this increased atomic activity can be best achieved when vibrating at subresonant frequencies (ref 8). The hysteresis curve for dynamic loading of a component is used to show that the material best absorbs ("dampens") the input energy at subresonant frequencies. At resonance, it is suggested that dampening effects are minimal and that the majority of input energy is converted to output vibration of the component.

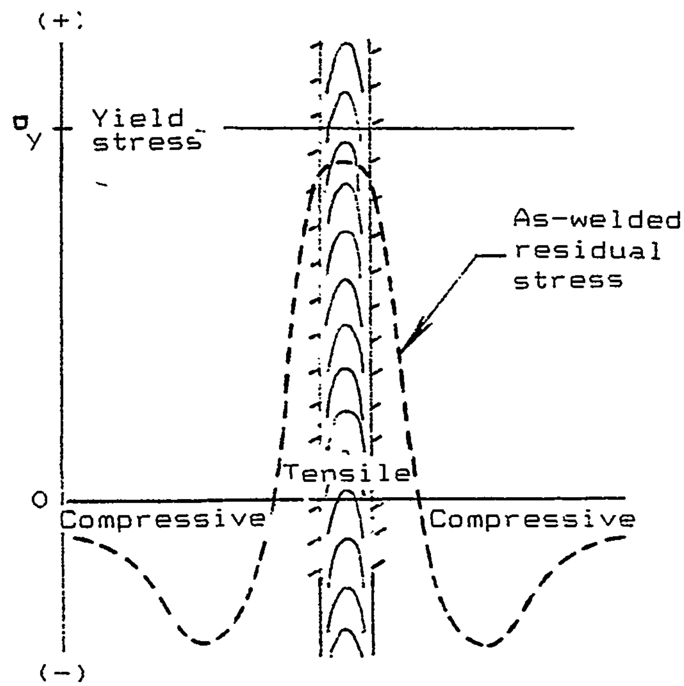


Figure 29. Residual stress distribution around a weld

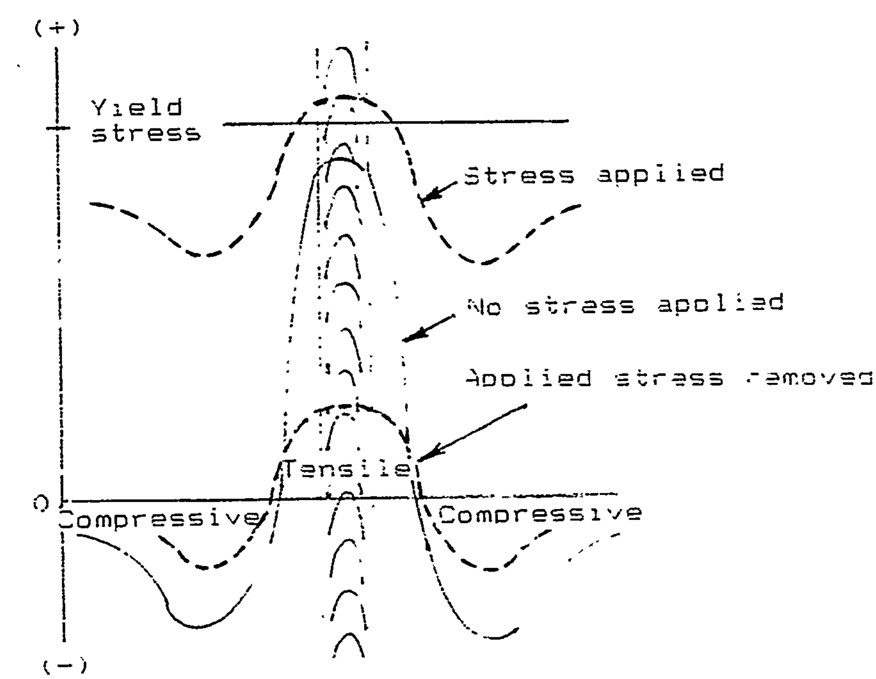


Figure 30. Effects of applied vibratory stress on the stress distributions around a weld (ref 13)

9.2 Using Vibratory Stress Relief

Vibratory stress relief can not be currently used as a substitute for thermal stress relief in most "code" work. In naval ship construction goverened by Mil-Std-1689(SH), thermal methods must be used when stress relief of weldments is specified. However, this does not prevent the use of vibratory methods on the many (in fact, great majority of) weldments that do not have stress relief requirements.

Similar to thermal stress relief, vibratory stress relief is most commonly used on completed weldments to relieve residual stresses prior to machining. If unrelieved, then as material is removed in the machining operation, those stresses which were internally balanced within the material become unbalanced and distort. Stress relief thus reduces the number of machining passes required and increases the achievable accuracy.

Vibratory stress relief offers significant advantages over thermal methods that include:

- Speed of operation. VSR on a weldment is normally accomplished within 1/2 to 2 hours.
- Portability of the machines. Equipment can be moved to the weldment.
- Virtually no size limitations. an large weldments, stress relief can be accomplished by moving the vibrator to a number of locations.
- No thermal effects such as scaling or distortion (as when not supported correctly in the furnace)

additionally, vibratory stress relief may be used during welding. Because the amplitude of vibration is small (normally about 1/32" from peak to peak), welding control is not hindered. Benefits from this application are suggested to include:

- Better weld flow. Resulting in faster welding with less filler metal required.
- Improved weld ductility and nigher rasistance to cracking.
- Reduced distortion in the weld.

Vibratory stress relief is reported to be effective on most carbon steels, stainless steels, aluminum alloys, hardened or cast materials (where thermal stress relief could adversely affect properties) (ref 8). It is reportedly not effective on copper, copper alloys or cold-worked metals (ref 9).

9.3 Equipment Description and Operation

Vibratory stress relief equipment generally costs within the range of $8,000 to $25,000 dependent on the size of vibrator required and whether charting capabilities are included.

Equipment consists of three basic coinponents: (1) a vibrator (motor with eccentric weights) for inducing the mechanical force, (2) a transducer for measuring the amplitude of vibration, and (3) a control console for regulating the vibrator speed and readout of the transducer feedback. Power is supplied from a 120v or 240v outlet.

Operation of the equipment is reactively simple and can be easily learned within a few hours. The weldment is first set on some type of isolating support such as rubber pads, wood blocks or old tires. The vibrator is clamped to a rigid part of the weldment. The transducer is clamped on the opposite side of the weldment, preferably on a different member, to measure the furthest effects of the vibration.

Once setup, the speed of the vibrator is gradually increased until a resonant peak is found. This peak is identified by a significant increase in the amplitude of vibration and is shown on the control console readout. The speed of the vibrator is then increased further to similarly identify additional resonant peaks.

Three dominant peaks are then chosen and treated for a period of approximately 10-20 minutes each.

In addition to these standard equipment items, some manufacturers provide an x-y recorder for identifying when the stress relief process is complete. Its usage is based upon the theory that a Weldment with high residual strssses will be more rigid than if stress-free (ref 36). This increased rigidity poroduces higher resonant frquencies.

As stress relief occurs, the rigidity of the weldment is reduced and is shown as a change in its resonant frequencies. The x-y plotter is used to produce charts before and after treatment to visually show these changes. AS stress relief of the weldment takes place, resonant frequencies will change as one or both of the following:

O The amplitude of the resonant peaks will increase

O The frequency of the resonant peaks will decrease.

These effects were observed in the vibratory stress relief treatment of two identical mild steel knee braces in a machine shop in Poydras, LA. In this shop, a VSR-790 system supplied by VSR Inc., Neponset, IL., is used routinely on weldments prior to machining. Approximate size of the knee braces was 2000 lb and triangular with 10 x 6 ft legs as shown in Figure 31.

For the first brace, the vibrator was initially placed in the center of the long leg (position A in Figure 31). An initial run of the vibrator from 1000 to 5000 rpm was made to graph the resonant frequencies prior to treatment (the VSR-79O system makes this run automatically at a rate of 10 rpm/see). The two highest peaks were then treated for 15 minutes each. After treatment, a second run was graphed for comparison, and is provided in Figure 32 (graphs were actually plotted on plain white paper -- axes were established by the authors for illustrative purposes). As seen, a distinct change in the resonant frequencies was observed. Resonant peaks both increased in height and decreased in frequency as reported would occur with residual stress relief.

On the same brace, the vibrator was then moved to the center of the shorter leg (position B) . In this. position three peaks were treated. As shown in Figure 33, a much reduced affect occured on the first two peaks as compared to the changes that were observed with The initial treatment of the bracs vibrator in position A). For unexplained reasons, the third resonant peak was removed altogether.

The reduced effect of the second treatment (position B) on the resonant peaks as compared to the initial treatment (position A) indicates that the majority of stress was relieved in the initial treatment.

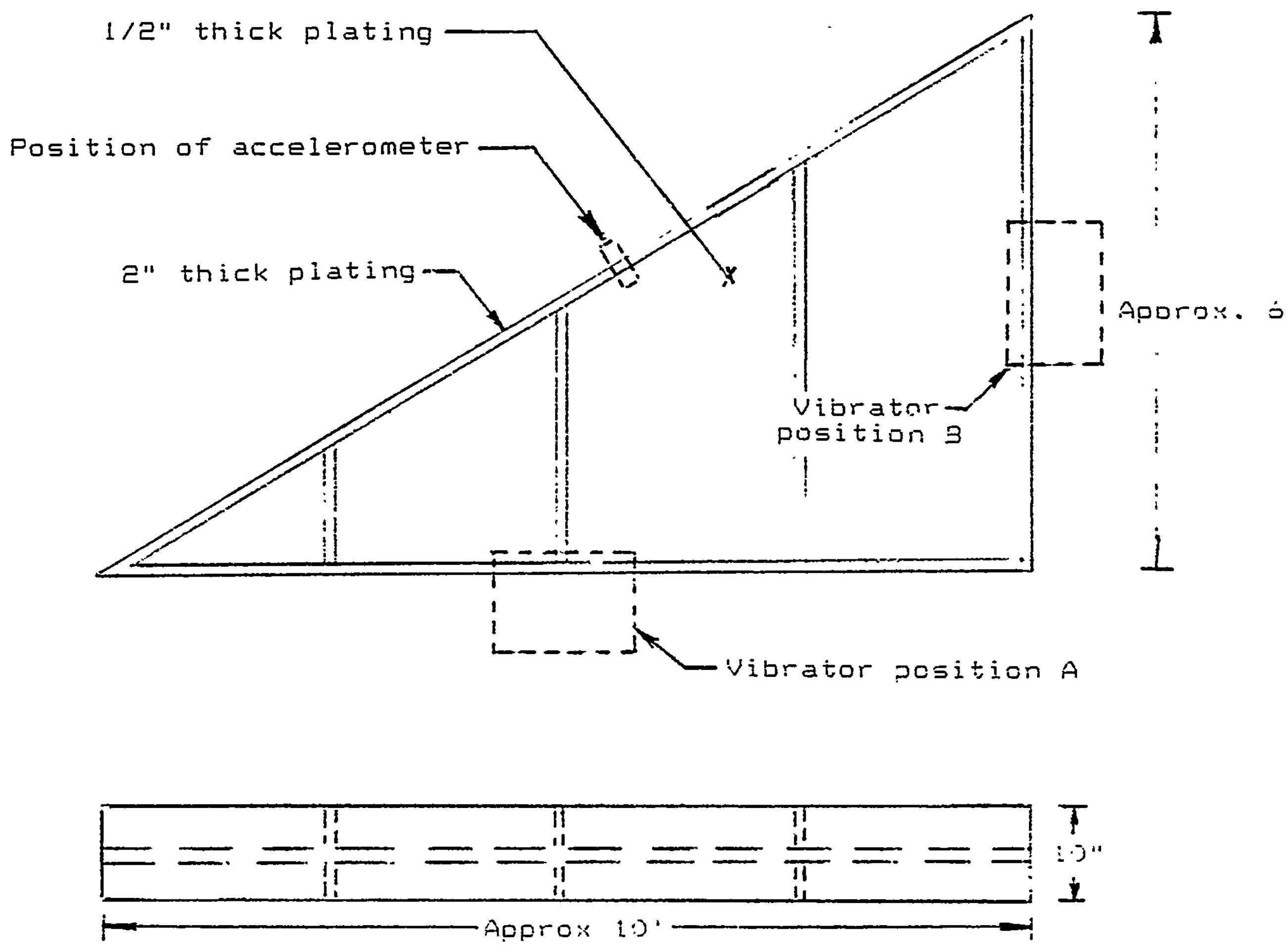


Figure 31. Knee brace, approximately 2000 lb, vibratory stress relieved prior to machining

Figure 32. 1st knee brace, 1st treatment, vibrator located in position A

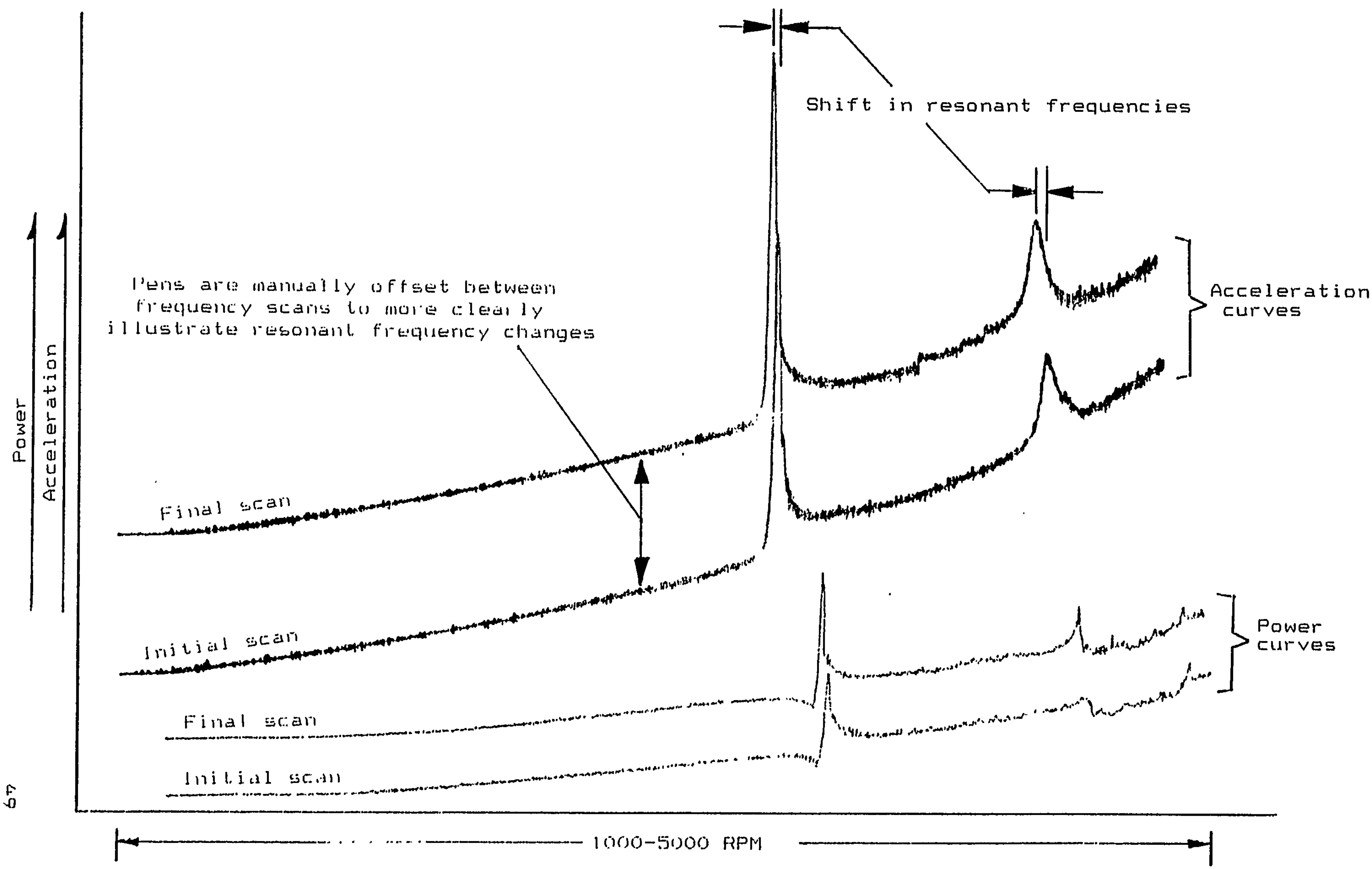


Figure 33. 1st knee brace, 2nd treatment, vibrator located in position B

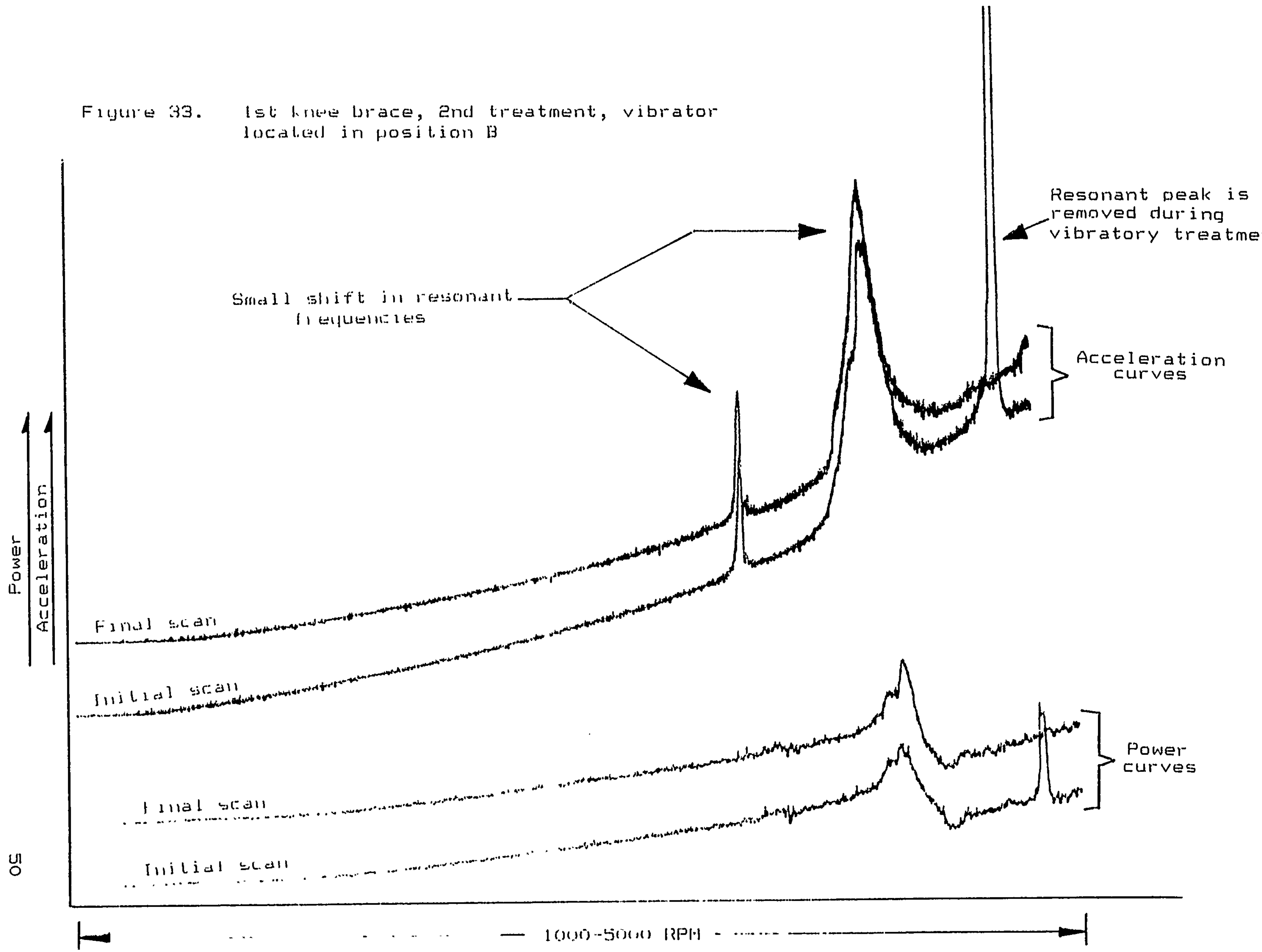


Figure 34. 2nd knee brace, 1st treatment, vibrator located in position B

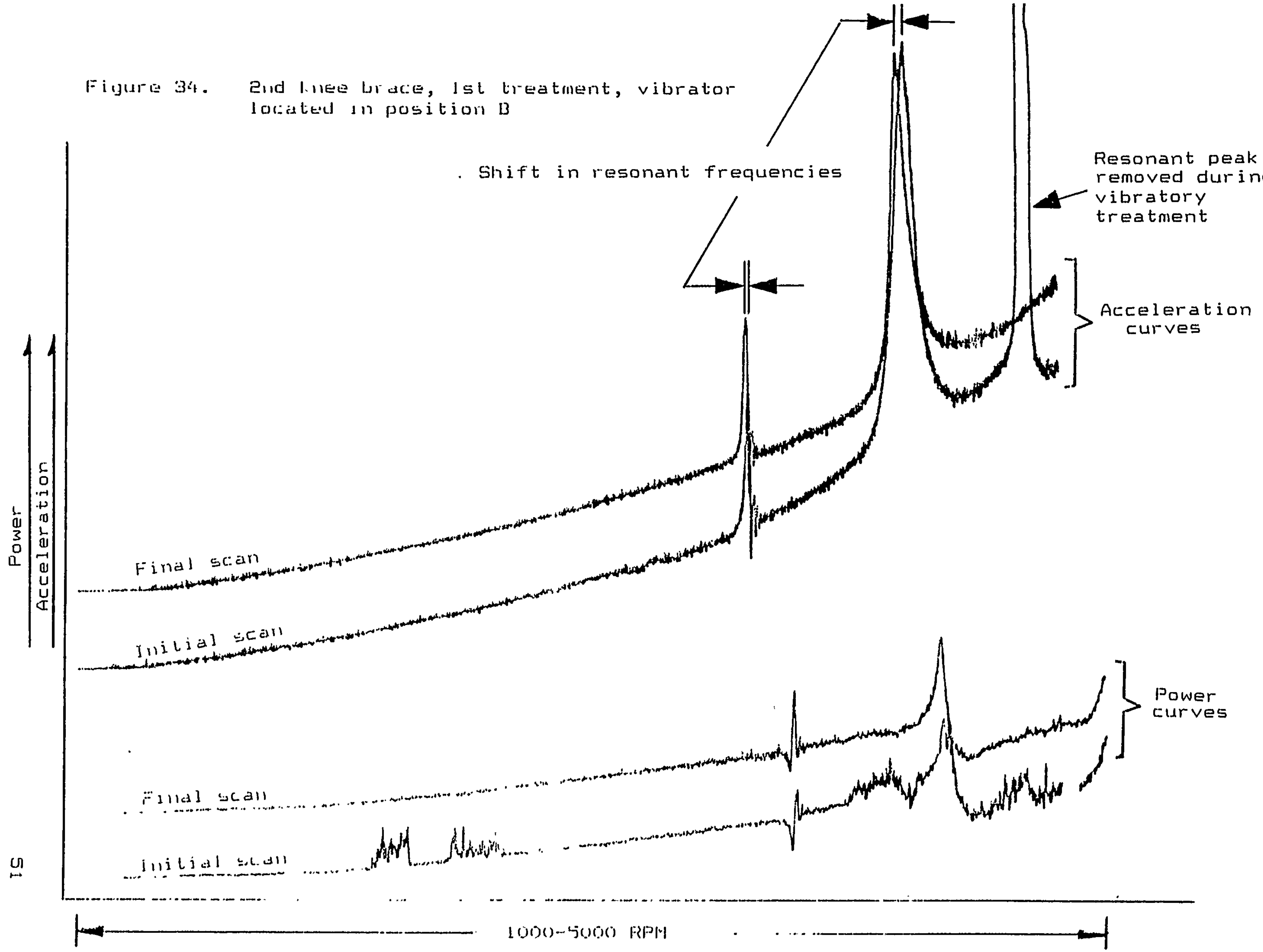
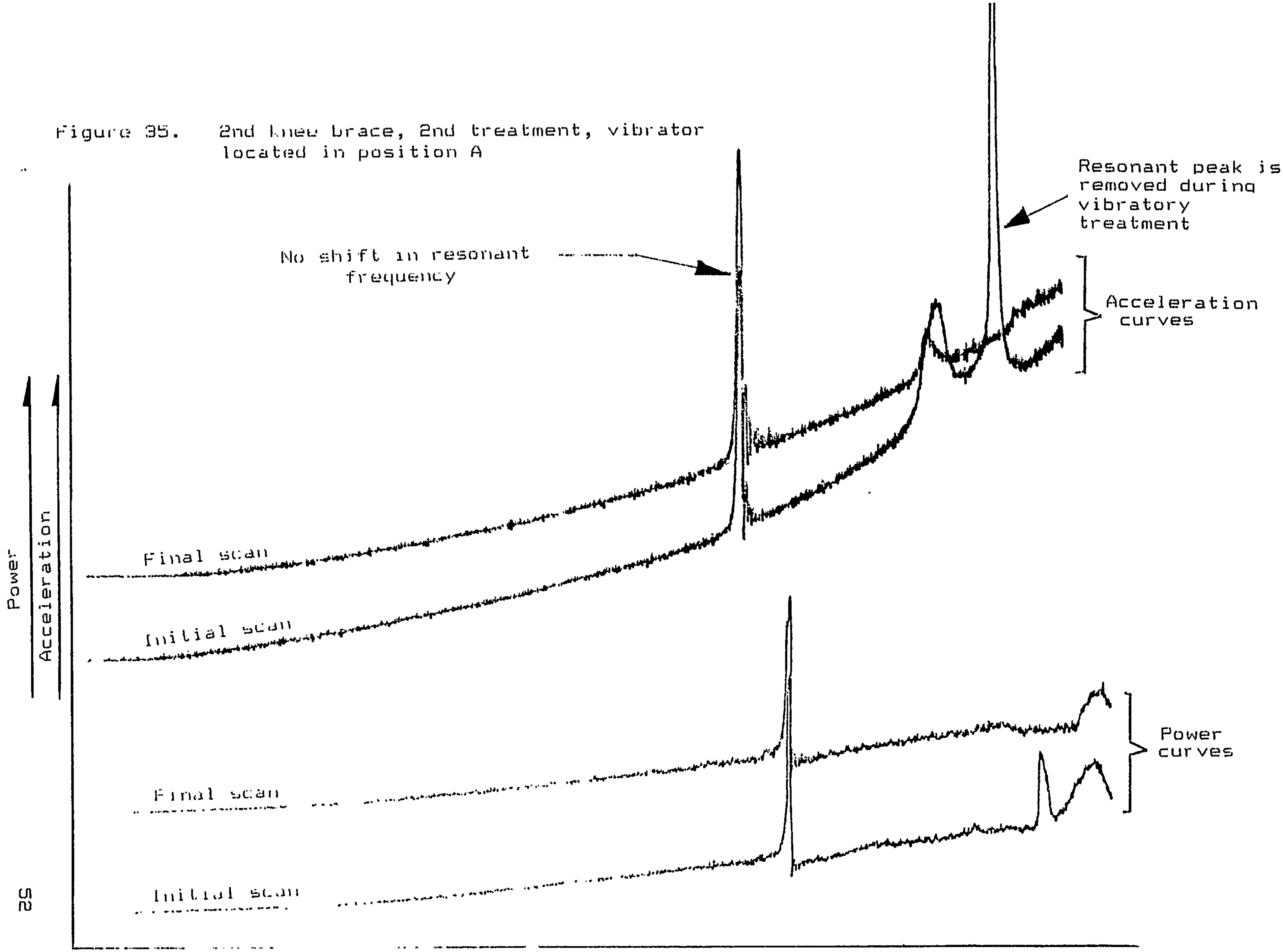


Figure 35. 2nd knee brace, 2nd treatment, vibrator located in position A



On the second brace, the positioning of the vibrator for each treatment was reversed (position B first, and then position A). Figures 34 and 35 provide the graphs for these treatments. As shown, a reduced effect was observed again in the second treatment as compared to the first. In both vibrator positions, the third resonant peak was removed altogether.

Thus, on the second brace, even with the vibrator positions reversed between treatments, the same reduced effect on the resonant peaks was observed in the second treatment as compared to the first.

9.4 Resonant Vibration During Welding

9.4.1 Test method

In this effort, the effects on distortion of resonant vibration during welding were investigated. Twenty-five pairs of test plates were butt welded while being vibrated at resonance. Angular distortion measurements were taken and then compared to similar measurements on 25 non-vibrated pairs.

Formula 62 stress relief equipment supplied by Stress Relief Engineering Company, Costa Mesa, CA. was used to obtain resonance. The equipment consisted of a variable speed vibrator, an accelerometer (transducer) for measuring the amplitude of vibration, and a control console for adjusting vibrator speed and amplitude meter for output of the accelerometer.

As shown in Figure 3, the test setup consisted of a 12 foot I-beam fixture simply supported on its lower flange by two 6x6 inch wooden blocks (set 3' in from each end) that served as isolation from the floor during vibration. Test plates were 12x6 inch mild steel with a 45 degree bevel and 1/l6 inch land. The test plates were paired, set level and tacked in two places. one inch from each end. Any angular change due to the tacking (during which there was no vibration) was measured for later accountability.

The vibrator was clamped to the top flange at one end of the fixture. The accelerometer was clamped to the other end. Eight of the test plate pairs (9 on the last run) were evenly spaced approximately 4 inches apart and were clamped along the fixture length. For both the vibrated and non-vibrated pairs,

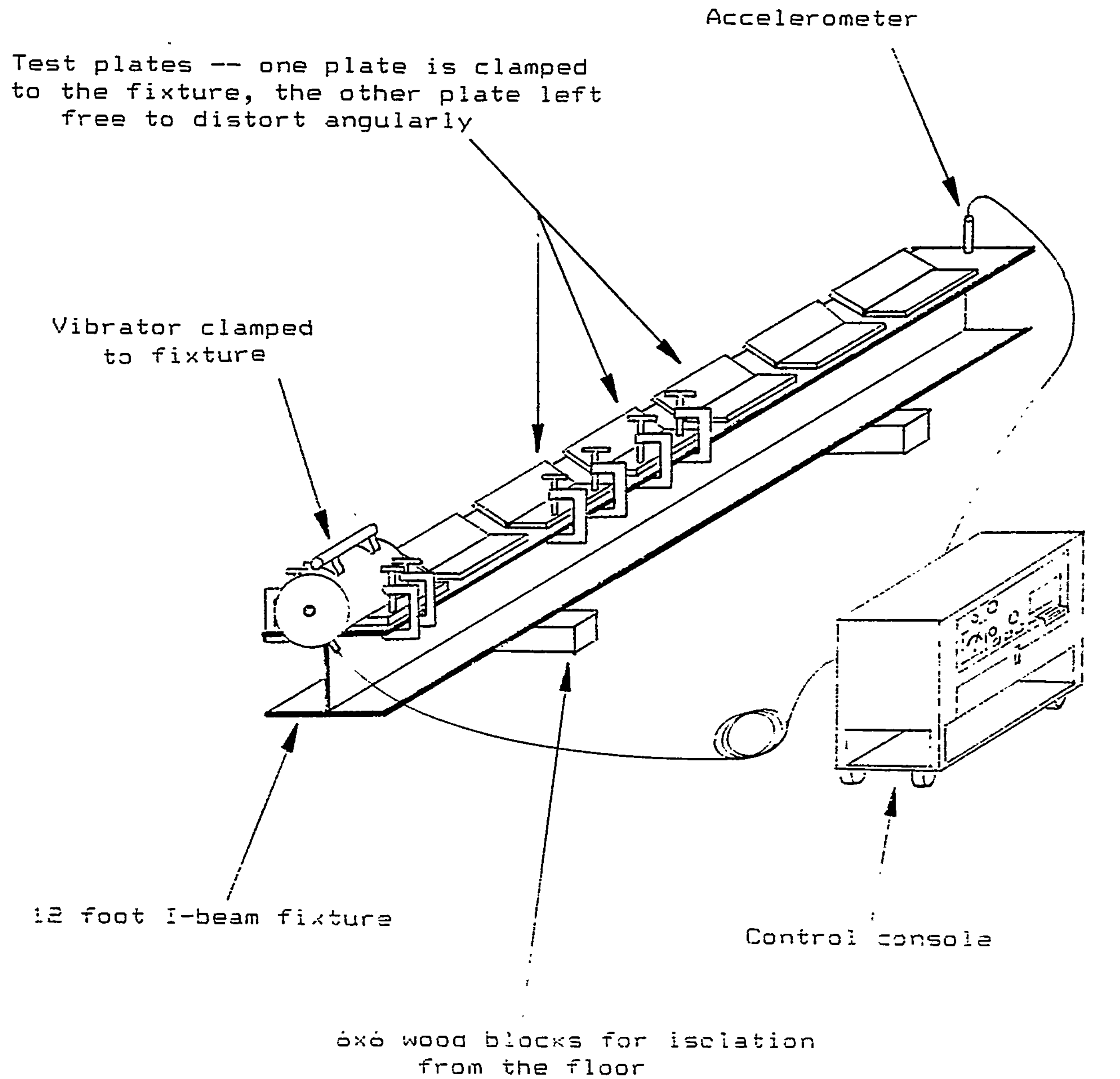


Figure 36. Test setup for determining the effect of resonant vibration during welding on angular distortion

only one plate was clamped to the fixture during welding to allow free movement (angular distortion) by the other plate, as shown in Figure 36.

By slowly increasing the speed of the motor using a potentiometer on the control panel, vibration frequency was slowly increased until each resonant frequency within the speed range of the vibrator was determined. An indication meter on the control panel connected to the accelerometer indicated the resonant point (at this frequency a vibrator speed increase or decrease would cause a drop in the amplitude of vibration). The resonant frequency with the highest amplitude was chosen for the test setup. Prior to welding, the accelerometer was removed to prevent damage to it from the welding current.

Six weld passes using shielded metal arc welding with 7018 electrodes were made completing a pass on each of the clamped test plates before continuing to the next pass. after welding, a minimum cooling period of one hour was allowed prior to taking measurements. Measurement of the vertical movement of each distorted plate was taken at the center and each end using a dial caliper, and angular distortion calculated.

9.4.2 Analysis of Measurments

(Angular distortion measurements for both the vibrated and non-vibrated samples are shown in Table 1. A frequency distribution of these measurements is shown in Figure 37. From these measurements, sample mean and standard deviation values are calculated as shown below:

	with vibration	without vibration
sample mean =	3.39 deg	8.63 deg
sample standard deviation =	(0.48 deg	0.47 deg
minimum distortion =	6.92 deg	7.41 deg
maximum distortion =	9.26 deg	7.72 deg

As shown, a small reduction in angular distortion was observed with the plates vibrated during welding versus those not vibrated. Mean angular distortion with vibration was 8.39

Table 1. Angular distortion measurements: Test plates with and without vibration during welding

I. Resonant Vibration During Welding

Test Plate #	Total Angular Change (Degrees) 1	2	3
1	8.53	8.23	8.43
2	8.40	7.92	8.06
3	9.26	8.49	8.73
4	8.41	3.38	3.65
5	9.19	3.33	8.54
6	3.40	9.17	3.16
7	3.77	3.61	3.81
8	3.30	8.49	3.80
9	9.13	8.93	3.85
10	3.66	8.62	8.99
11	3.26	8.25	3.26
12	7.78	7.22	7.35
13	9.49	3.47	8.65
14	7.70	7.74	8.25
15	8.79	9.15	3.49
16	8.70	5.78	9.05
17	8.72	5.32	3.19
18	8.24	3.48	7.61
19	9.31	3.74	3.73
20	7.78	7.59	7.61
21	3.77	3.20	5.21
22	7.30	6.72	7.38
23	3.27	5.29	3.48
24	8.37	3.45	3.27
25	3.48	3.11	3.25

II. No Vibration During Welding

Test Plate #	Total Angular Change (Degrees) 1	2	3
26	9.37	8.72	9.16
27	8.34	7.97	3.19
28	8.40	8.22	3.64
29	8.59	8.50	8.51
30	3.42	3.41	3.85
31	5.79	5.93	9.17
32	3.26	3.06	3.32
33	9.10	3.57	9.12
34	5.37	8.05	3.83
35	9.01	3.90	9.25
36	7.42	7.41	7.70
37	5.59	7.95	3.40
38	3.05	7.92	3.15
39	9.05	8.93	9.28
40	9.17	5.30	[illegible]
41	5.52	3.46	5.72
42	9.10	5.73	9.32
43	3.72	5.55	3.74
44	9.10	9.08	[illegible]
45	9.24	3.74	[illegible]
46	3.73	5.38	[illegible]
47	5.84	3.97	9.21
48	3.38	[illegible]	3.35
49	5.22	3.25	3.51
50	3.20	5.19	3.34

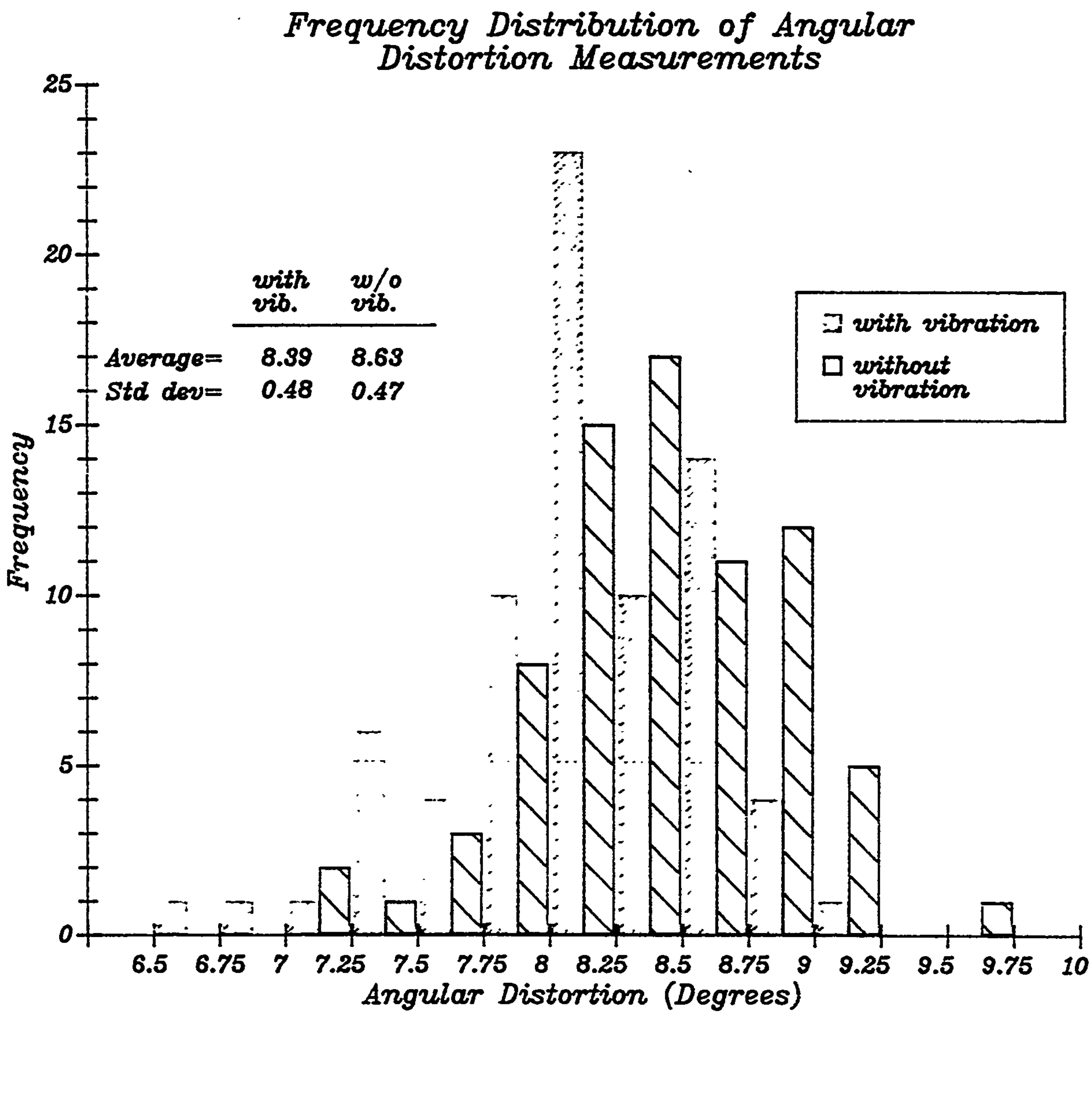


Figure 37. Frequency distribution of angular distortion measurements: Test plates with and without vibration during welding

degrees, while without vibration was 8.63 degrees. The extent of this reduction may be calculated as,

$$(8.A3 - 8.39)/8.63 = 2.78\ \% \quad \text{reduction}$$

To insure that this reduction is not simply a function of the variability associated with the sampling effort, the sample distributions are tested statistically. A test statistic value of z = 3.094 establishes that a mean reduction in distortion exists at a 95 % level of confidence (see Appendix for explanation of statistical methods).

From the variability (standard deviation) measured in each of the samples, the range in which this reduction can be expected to fall 95 % of the time can be calculated as,

$$0.239 \ +/- \ 0.151 \text{ degrees}$$

or expressed as a percentage,

$$2.78 \ +/- \ 1.75 \ X \ \text{reduction}$$

Thus, as determined, a reduction in angular distortion can be expected in the range of 1.03 to 4.53 percent at a 95 percent level of confidence.

9.5 Resonant Vibration After Melding

9.5.1 Test method

Tune distortion effects of resonant vibration applied to completed weldments was investigated. Test plates that had been previously welded without vibration were subjected to resonant treatment. Measurements were taken after the treatment and compared to previous measurements to determine whether any change had occured.

Fifteen of the sample pairs which had been previously welded without vibration were randomly chosen. Eight of these pairs were then clamped to the fixture (7 in the second run) in the same manner as in the previous testing: one plate clamped firmly and the other left free to distort.

The vibrator was clamped to the top flange at one end of the fixture. The accelerometer was clamped to the opposite end. The speed of the vibrator was slowly increased until all resonant frequencies within its speed range were determined. Vibratory treatment was then accomplished at the two resonant frequencies with the highest amplitudes for a period of 20 minutes each.

after treatment, angular distortion measurements were taken and compared to measurements taken prior to treatment.

9.5.2 Analysis of measurements

Angular distortion measurements taken before and after vibratory treatment of the test plates are provided in Table 2. A frequency distribution of these measurements is provided in Figure 38. From these measurements, sample mean and standard deviation values are calculated as shown below:

	before vibration	after vibration
sample mean =	7.94 deg	7.94 deg
sample standard deviation =	0.51 deg	0.51 deg
minimum distortion =	6.77 deg	5.67 deg
maximum distortion =	8.80 deg	3.72 deg

As seen from these figurss and the summary values above, virtually no change was observed in the distorted angles of the test plates as a result of the vibratory treatment. Mean values of the samples remained the same, equal to 7.94 degrees. Stanclard deviation values similarly remained the same, equal to 0.51 degrees.

Table 2. Angular distortion measurements: Test plates before and after vibration.

Test Plate #	Before Vibration (degrees) 1	2	3	After Vibration (degrees) 1	2	3	Difference between Before and After Measurements (degrees) 1	2	3
26	8.08	7.92	8.32	8.23	8.02	8.55	-0.15	-0.10	-0.2[illegible]
27	8.03	7.67	7.95	7.80	7.59	7.95	0.23	0.08	0.00
28	7.37	7.19	7.62	7.40	7.24	7.56	-0.03	-0.05	0.06
29	8.24	8.05	8.12	8.01	7.96	8.09	0.23	0.10	0.03
30	7.97	7.65	8.25	8.07	7.31	8.13	-0.10	0.35	0.13
31	8.43	8.36	8.74	8.39	8.36	8.72	0.04	0.00	0.02
32	7.41	7.52	7.98	7.45	7.41	7.81	-0.04	0.11	[illegible]
33	8.65	8.25	8.70	8.53	8.19	8.55	0.12	0.06	[illegible]
34	7.27	7.19	7.44	7.32	7.19	7.51	-0.05	0.00	-0.07
35	8.55	8.45	8.30	8.52	8.43	8.72	-0.02	0.02	0.12
36	6.77	6.79	7.09	6.67	6.26	7.08	0.10	-0.07	[illegible]
37	8.24	7.80	8.23	8.32	8.10	8.23	-0.08	-0.29	-0.05
38	7.49	7.38	7.65	7.91	7.37	7.50	-0.42	0.01	0.15
39	8.25	8.11	8.51	8.34	8.40	8.61	-0.10	-0.29	-0.11
40	8.04	7.63	8.13	8.20	7.79	8.30	-0.16	-0.11	-0.17

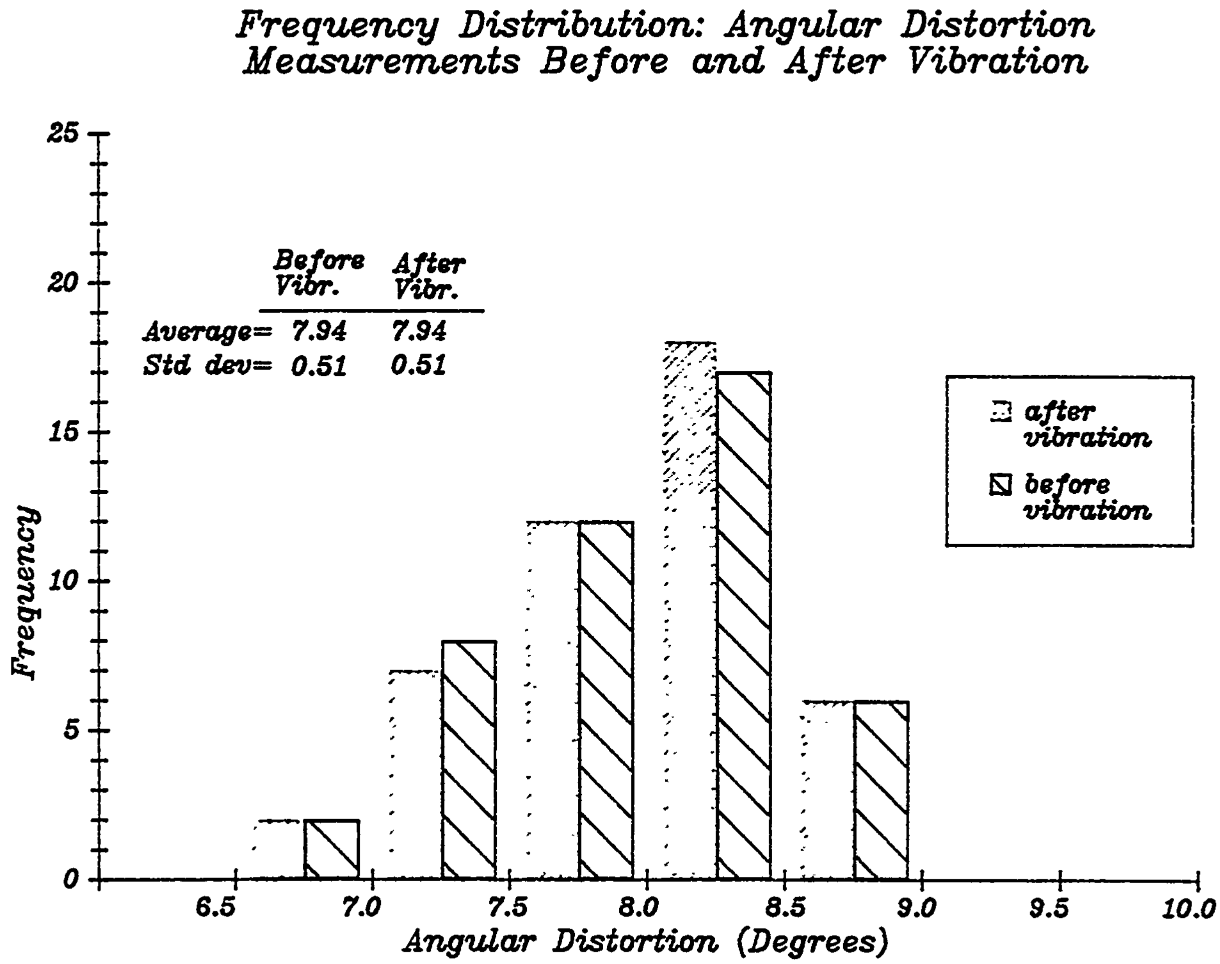


Figure 38. Frequency distribution of angular distortion measurements: Test plates before and after vibration

9.6 Metallographic Inspection of Test Plates

Test plates were submitted to Ingalls welding lab for metallographic inspection of the welds. Five plates were randomly chosen from each of the following groups:

(1) Resonant vibration applied during welding.

(2) No vibration during welding, resonant treatment applied after welding.

(3) No vibration applied during or after welding.

Specimens were submitted without identifying to which group they belonged.

No apparent differences were found in the grain sizes of the various groups. Specimens subjected to vibration could not be distinguished from those that were not subjected to vibration. Figures 39, 40 and 41 provide the microstructure photographs (magnification setting of 200x) for each of the three groups listed above, respectively. The slight variation in the grain color of each specimen may be attributed to a difference in the degree of etching or in the intensity of applied light.

9.7 Summary of Results

The application of resonant vibration during welding showed that a reduction in distortion did occur, but that this reduction was small **(=** only 2.78 % in the angular chanqe of the test plates). Thus, large reductions in weld distortion simpl, through the use of resonant vibration during welding cannot be expected. where this reduction is required, more canventional distortion control methods such as the use of restraint and weld sequencing must still be applied.

The distortion effects of resonant vibrator, treatment applied to completed weldments was additionally investigated. Results showed that this treatment produced no distortion in the weldifients. Unlike thermal stress relief treatments which can potentialy cause distortion (particularly if the weldement is not supported correctly), vibratory treatments apparently dose no problems in this respect

NITAL 1000X

Figure 39.

Weld microstructure at 1000x : Test plates vibrated at resonance during welding

NITAL 1000X

NITAL X1000

Figure 39. (continued)

NITAL 1000X

Figure 40.

Weld microstructure at 1000x : Test plates not vibrated during or after welding

NITAL 1000X

NITAL 1000X

NITAL X1000

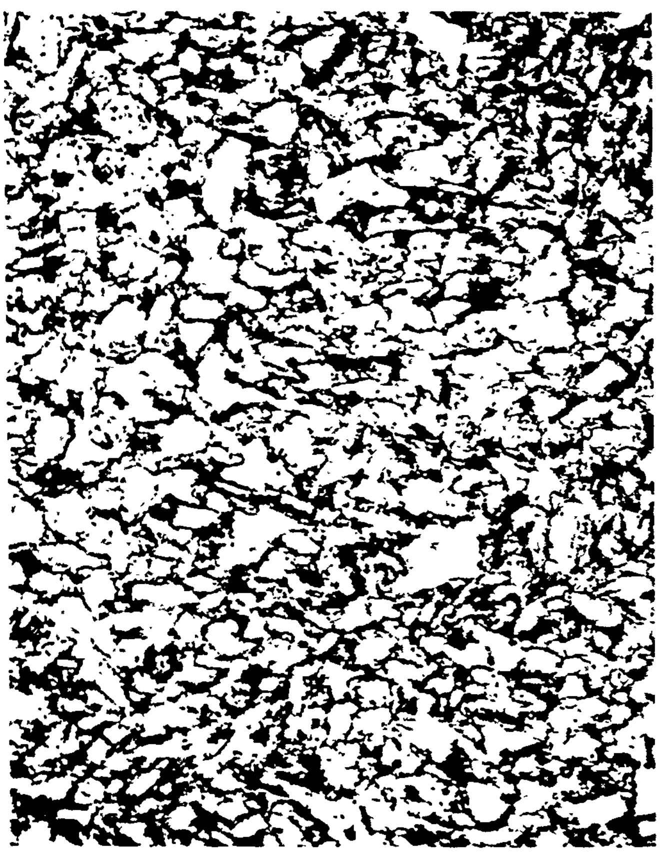
Figure 40. (continued)

NITAL X1000

NITAL X1000

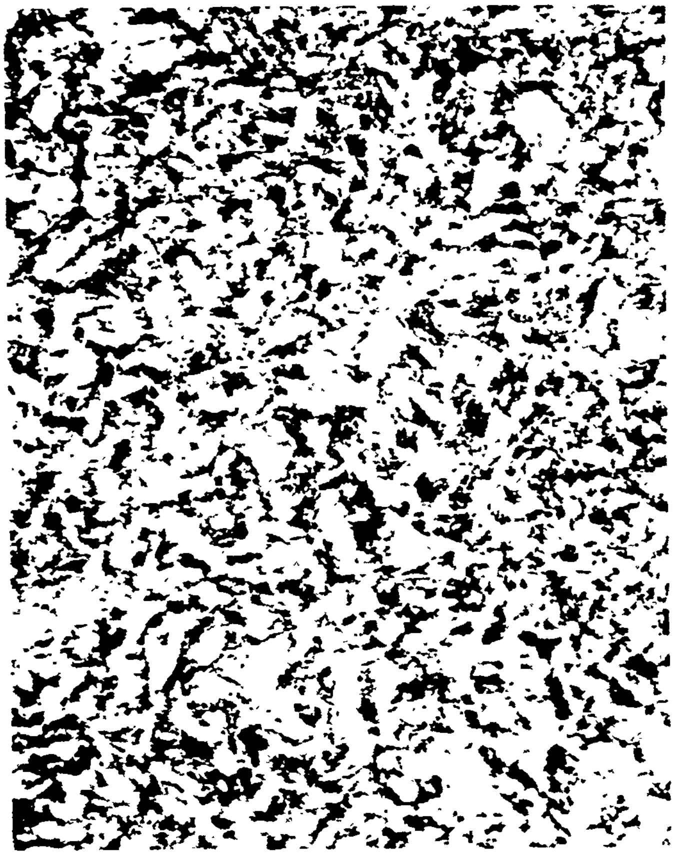
Figure 41.

Weld microstructure at 1000x : Test plates-not vibrated during welding, vibrated after welding



NITAL X1000

NITAL X1000



NITAL 1000x

Figure 41. (continued)

NITAL 1000X

Measurement of magnitudes and direction of residual stresses in metal structures requires the application of laboratory techniques which are difficult to implement on structures in the field. Such measurements were beyond the scope of this project. However, measurements and curve plots of amplitudes and frequencies of vibrational energy produced distinct evidence of significant changes to the resonance characteristics of the knee brace structures which may correlate to relief of residual stresses.

That distinct changes actually occurred is further evidenced by the fact that a repetition of input vibrational energy did not produce any further changes; also, it was found that the changes produced in a second structure were very similar to the first structure, regardless of the fact that the position of the vibrators were reversed.

However, in contrast to these observations, metallographit inspection of the test welds did not show a discernible difference in the grain structure of the vibrated and non-vibrated samples.

It is possible that residual stresses could be measured more directly with X-ray diffraction and/or stirain gages and those measurements correlated to those changes in rasonance behavior shown in the response curves. That work is recommended for the future in order to gain a better understanding of the physics of stress relief of welded structures by resonant or subresonant vibration.

10.0 Presetting of Innerbottom Units

When shrinkage occurs in a weldment at some distance from its neutral axis, a bending moment is created. This moment produces a “bow”, or bending distortion, in the weldment. Figure 42 shows the bending distortion produced from the fillets in a tee section.

In more complex weldments, bending distortion may be viewed as the combined effect of the shrinkage produced at each of the individual joints. Each joint, as it is we: ded, creates a bending moment around the neutral axis of the weldment. Joints that are on opposite sides of the ax axis produce offsetting bending moments. The net bending moment of the total joints combined produces a bending distortion. If the balance of these forces can be determined, then the direction of the bending distortion can be easily predicted.

Limiting factors exist that affect the amount of bending distortion produced. It is the net force applied to the moment arm which determines the severity of the distortion. The rigidity of the material in the direction resisting movement, the weight of the structure, and any applied restraints all tend to reduce the net force. Weld size and the type of welding process used can reduce or or increase the net force applied.

For simple weldments, such as a built-up tee section. prediction of both direction and magnitude of produced distortion is easily accomplished. For slightly more complex weldments, prediction requires the use of computer modeling. For very complex weldments, quantification of distortion is not possible even with camputer mode due to a lack of definition of the various interrelationships of restraints and forces. Precise definition is rendered impossible for production purposes due to the inability to maintain exact weld sizes and the impractibility of obtaining exact fit in all locations. Numerous lesser factors contribute to the inability to precisely

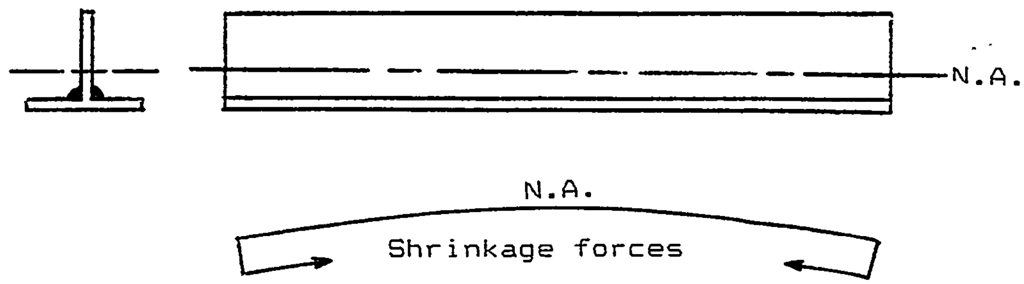


Figure 42. Bending distortion from fillets in a tee

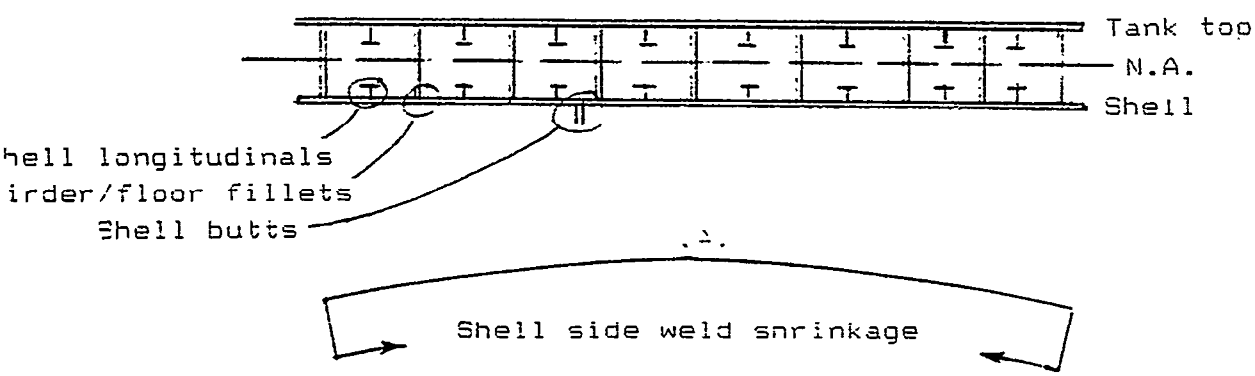


Figure 43. Innerbottom unit bending distortion from shell side welding

predict the amount of distortion, such as the change in stresses due to the tempering and annealing effects of consequent welds on completed welds and the differences in stress configurations of purchased steels. Direction can still be predicted based on previous problems and examination of those components which resist distortion.

The use of presetting of flat innerbottom units at Ingalls is the result of problems encountered in construction of units on the initial LHD contract.1 In these cases, a "crowning" effect was produced transversely. This crowning effect can be explained as bending distortion of the units resulting from welds on the shell side, as shown in Figure 43. Shrinkage forces from these welds combined to create a bending moment that "bowed" the innerbottom units. Specifically, these welds may be categorized as two types: (1) shell plating butts, and; (2) floor/girder/longitudinal fillets to the shell plating.

To correct for this distortion, presetting was used on the innerbottom units of the next hull. A preset of one inch was used over the 80 ft width of each of these units. his presetting amount was based upon the crowning effeccts observed on the initial hull. In retrospect, this presetting amount proved to be a fairly accurate estimate and one that was quite repeatable for each of the innerbottom units. A construction sequence was used that maintained this preset amount in each innerbottom unit until all the tank top butt and fillet welds were completed.

10.1 Construction Sequence

Each of the three innerbottom units measured for the purposes of this report (#301, #302, and #307) were fabricated in the same manner. Overall size of each unit was approximately 80 ft transversely and 56 ft longitudinally. Each was preset one inch over the 80 ft width.

Plating for the tank top was fabricated in the panel line as two half-units (port and starboard halves). Tank top longitudinal were then fit and welded out.

(1) The LHD's are 36,000 ton U.S. Navy surface ships.

From the panel line, each tank top unit was moved to a flat fixture on which liners were located to provide the preset condition. Liners were 1" high along the longitudinal center of each half-unit, tapering down to O" at the panel edges. The panel edges were then restrained using clips and wedges. Although restrained vertically, these clips allow movement laterally, preventing excessive residual stresses.

Girders subassemblies with attached floors on one side were then fit to the tank top. Girder/floor subassemblies were fit beginning at the center of each tank top half unit progressing outward. After completion of fitting to the tank top of two adjacent girder/floor subassemblies the downhand fillet welds were made for the center section. Only after the completion of the downhand fillets of the adjacent subassemblies were the vertical girder/floor joints of the center subassembly fit and welded. This pattern was followed for each girder/floor subassembly until all vertical welds and tank top fillets were completed.

Restraint on the tank top units maintained the preset condition. Upon completion of this stage, each tank top half-unit was sent to blast and paint and then rerurned to the flat fixtures.

The two half-units were then fit together to form the complete innerbottom tanktop. A 1" liner was placed along the centerline of the unit to provide the same preset condition over the 80 ft width. The innerbottom edges wers restrained as previously accomplished with strongbacks and wedges. The centerline butt of the unit was accomplished using one-sided welding. The Final girder/Tloor vertical joints were fit and then welded progressing from the center of the unit outward (fore and aft). Restraints were then removed.

At this point, restraint used through the construction of the innerbottorn unit has maintained the preset conditions. The innerbottom unit is presset with a one inch "reverse *crown".*

The unit was next shipped to flat fixtures in a prs-outfitting area, shimmed to a 1" height at centerline, tapering to O" at the unit outboard edges. The plate edges were not restrained in this stage. Shell plating was then installed from the centerline outboard, fit to girders and floors (block weld), and butts made using one-sided welding. When all shell butts are complete, then the innerbottom unit was turned shipshape. No restraint was installed. The remaining girder, floor and longitudinal fillets to the shell were accomplished in the downhand position.

10.2 Flatness Measurements

Upon completion of weldout, measurements were taken at each girder and floor intersection using a level. Tank top plating thicknesses were compensated for so that each measurement was to mold line. The flat condition of each innerbottom unit was defined as a level plane intersecting the median measurement. All measurements were then rescaled as a variance from the median of that unit. Table 3 provides the variance from median measurements for each of the innerbottom units. A total of 136 locations were measured for the 301 and 307 innerbottom units, and 152 measurements for the 303 unit.

10.3 Analysis of Measurements

The effectiveness of presetting innerbottom units is determined in analyzing the variability of flatness measurements of each unit. The greater the variance from the median plane, the greater the bow of the unit.

For the innerbottom units observed, presetting provided satisfactory and consistent results on each unit. Quantitatively, these results are shown below for each innerbottom unit and all units combined as the percentage of total measurements inside 1/8", 1/4" and 1/2" ranges of variation:

Table 3. Variance from median plane for #301, #303, and #307 innerbottom units

INNERBOTTOM UNIT # 301, COMPLETE : VARIANCE FROM MEDIAN PLANE

Longitudinal (16 ths)

Frame	18	16	14	12	10	8	6	4	2	CL	2	4	6	8	10	12	14	16	18
73		7	6	4	-1	3	3	3	-1	-3	-3	-3	7	-5	-2	1	1	3	
74		8	4	3	-2	1	1	1	1	-3	0	-2	-4	-2	1	4	3	6	
75		5	4	4	-2	1	-2	1	0	-2	-1	0	0	0	3	6	7	3	
76		6	3	3	0	0	-3	0	1	-2	-2	1	2	1	3	7	6	7	
77		3	2	-2	-1	-3	-4	-2	-3	2	-2	2	2	1	3	5	9	8	
78		2	2	0	-3	-4	-7	-4	-3	-2	-1	0	4	0	1	4	9	7	
79		1	1	-1	-4	-6	-6	-5	-4	-4	-1	-1	-1	-2	0	0	7	2	
80		1	-1	-5	-4	-6	-10	-9	-6	-6	-4	-1	-4	-2	-5	-4	1	0	

INNERBOTTOM UNIT # 303, COMPLETE : VARIANCE FROM MEDIAN PLANE

Longitudinal (16 ths)

Frame	18	16	14	12	10	8	6	4	2	CL	2	4	6	8	10	12	14	16	18
81	-5	-2	1	-3	-8	-5	-5	-7	-4	1	-5	-2	-3	-2	-2	-2	-4	-5	-2
82	-2	2	1	2	-4	-6	-3	-2	-1	-4	-3	1	1	-2	-3	-3	-2	-1	-1
83	2	2	3	5	1	1	-3	0	0	-2	-2	0	0	0	2	1	1	-2	-2
84	1	2	4	8	1	0	-2	1	1	-2	-3	2	3	2	3	4	4	0	2
85	9	5	3	9	9	4	0	0	1	-2	-1	2	3	2	5	5	4	2	2
86	3	3	6	7	2	1	0	2	0	-2	-2	3	2	2	2	5	3	3	2
87	3	3	3	2	1	0	0	-1	-1	-2	3	3	-3	-2	-2	0	1	1	2
88	-3	-1	1	0	-1	-3	-2	-1	-4	-5	-7	-6	-6	-5	-5	-2	-2	0	0

INNERBOTTOM UNIT # 307, COMPLETE : VARIANCE FROM MEDIAN PLANE

Longitudinal (16 ths)

Frame	18	16	14	12	10	8	6	4	2	CL	2	4	6	8	10	12	14	16	18
65		-9	-4	-5	-4	-4	0	1	-2	1	-2	-3	-2	-1	0	-1	-5	-4	
66		1	-4	-2	-1	-1	1	-1	-1	0	-5	-2	0	1	2	1	-1	0	
67		2	4	1	1	4	3	1	-1	3	-2	0	0	2	2	1	2	5	
68		7	7	3	1	1	1	3	0	2	-2	2	2	3	3	3	4	[illegible]	
69		7	8	4	0	-1	-1	0	0	1	-1	2	1	4	4	2	1	3	
70		5	7	4	1	-1	3	2	1	0	0	0	2	4	2	1	2	2	
71		3	4	1	-1	-2	1	0	1	0	-1	-3	-2	-1	-2	-4	-2	0	
72		0	-1	-2	-4	-5	-7	-7	-9	-1	0	-5	-5	-5	-5	-8	-7	-5	

		Inner bottom Unit			
		301	303	307	all units
+/- 1/8"	=	48.5 %	59.2 %	60.3 %	56.1 %
+/- 1/4"	=	77.9 %	82.9 %	83.1 %	81.4 %
+/- 1/2"	=	97.8 %	97.4 %	97.8 %	97.6 %

As seen, nearly 80 percent of all measurements on each 80' by 56' innerbottom unit were within +/- 1/4" of the median, and 98 percent were within +/- 1/2".

Figure 44 shows the frequency distribution of measurements for each unit. Calculated standard deviation values emphasize the consistency observed in each of the units, denoting the repeatability of the process. Each standard deviation fell within a irange of only 0.038".

Further investigation showed that additional improvement could be made by (1) reducing the current presetting amount transversely, and (2) accounting for bending distortion observed longitudinally by means of additional shims.

From the measurements in Table 3, a common configuration can be observed for each of the innerbottom units. As seen, high (positive) and low (negative) measurements are common to specific aieas for each innerbattom unit. The result is a slight saddle-like configuration as shown in Figure 45. Explanation for this configuration can be traced to two causes: (1) not all of the preset condition is removed by the shell butt and fillet welding, and (2) some bending is occuring longitudinally.

To illustrate the first rause (all preset not removed), Figure 46 pravides sectional views across each frame of the 301 unit. To better view the general survature of each unit, measurements were best fit by a second order polynomial. This "smooths" the curvs to provide a view which is free of the clutter of the various points of lucalized distortion.

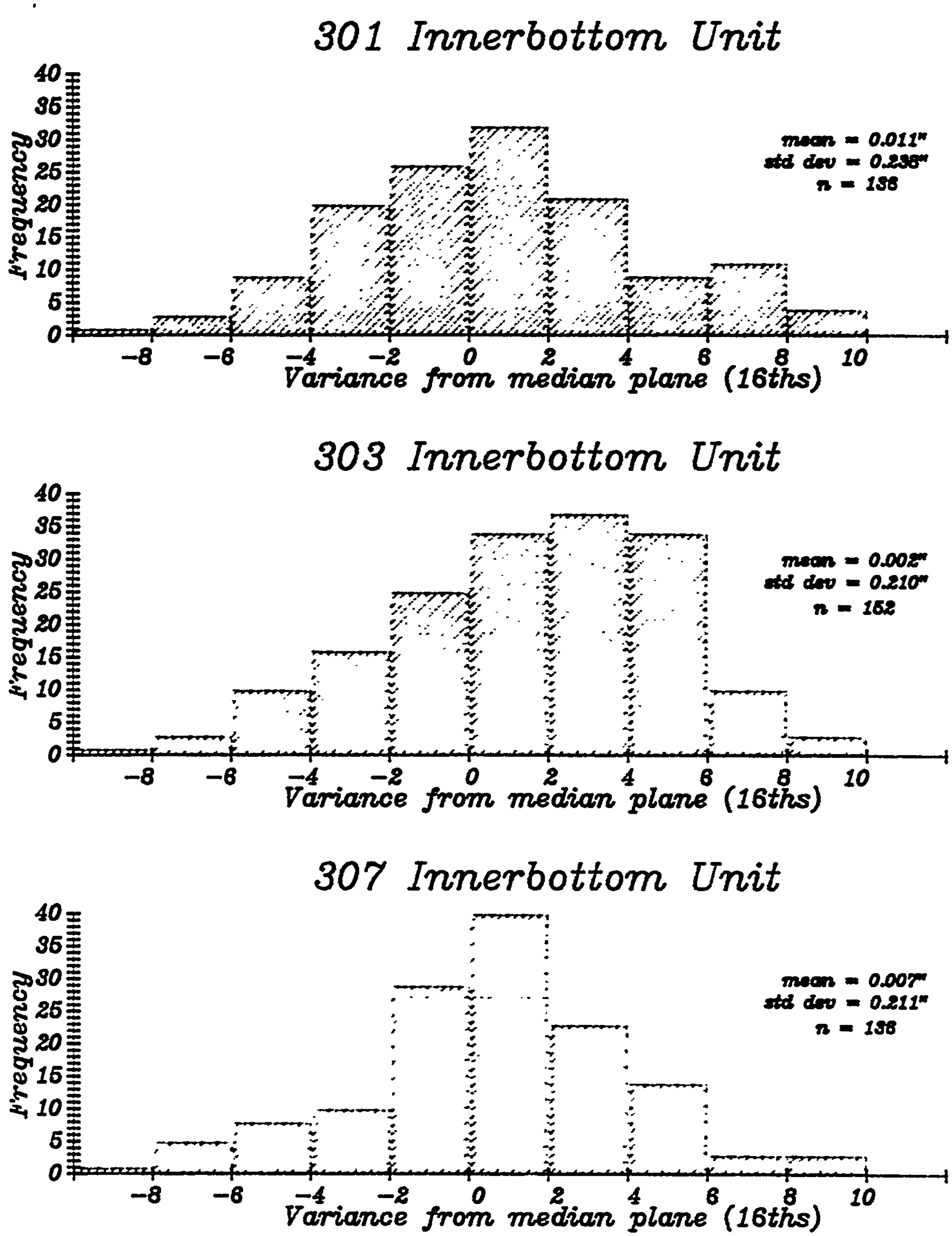


Figure 44. Frequency distribution of variances from median plane for #301, #303 and #307 innerbottom units

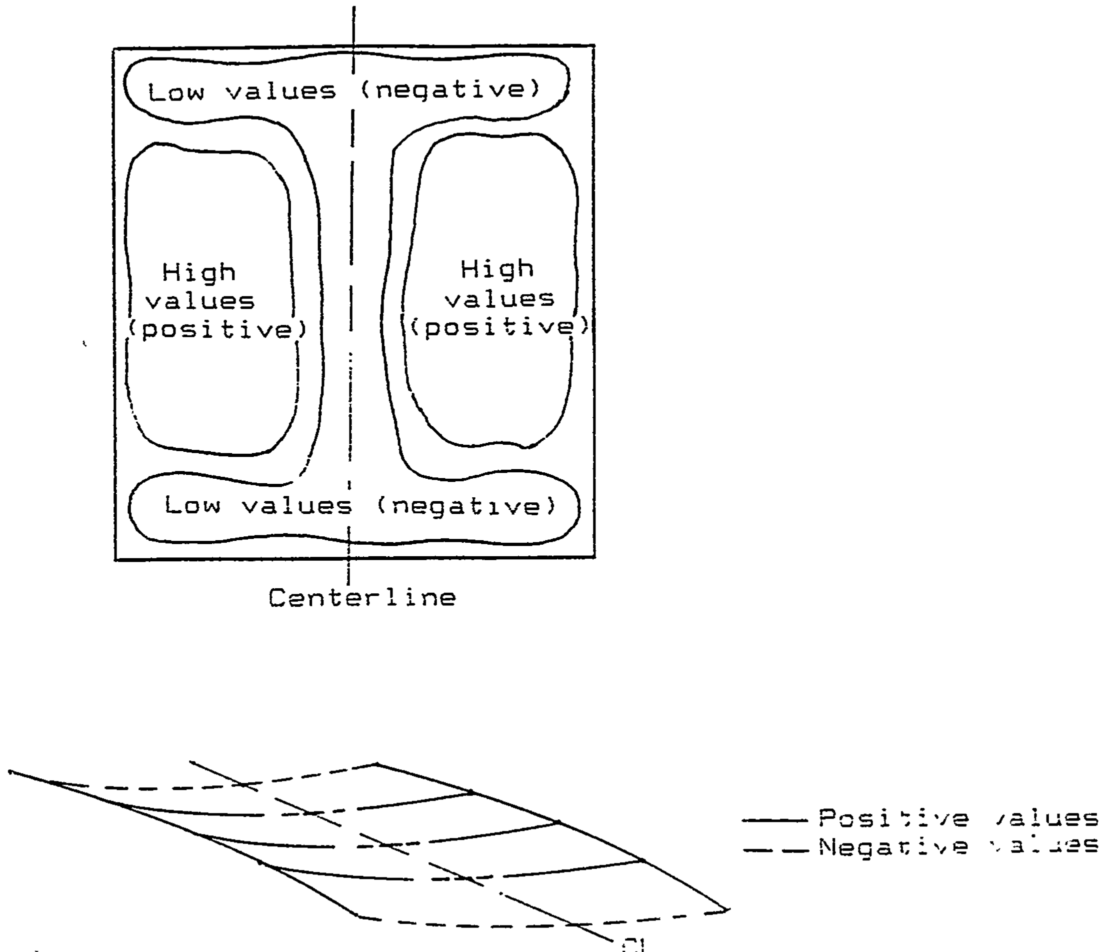


Figure 45. Distribution of values above and below median plane

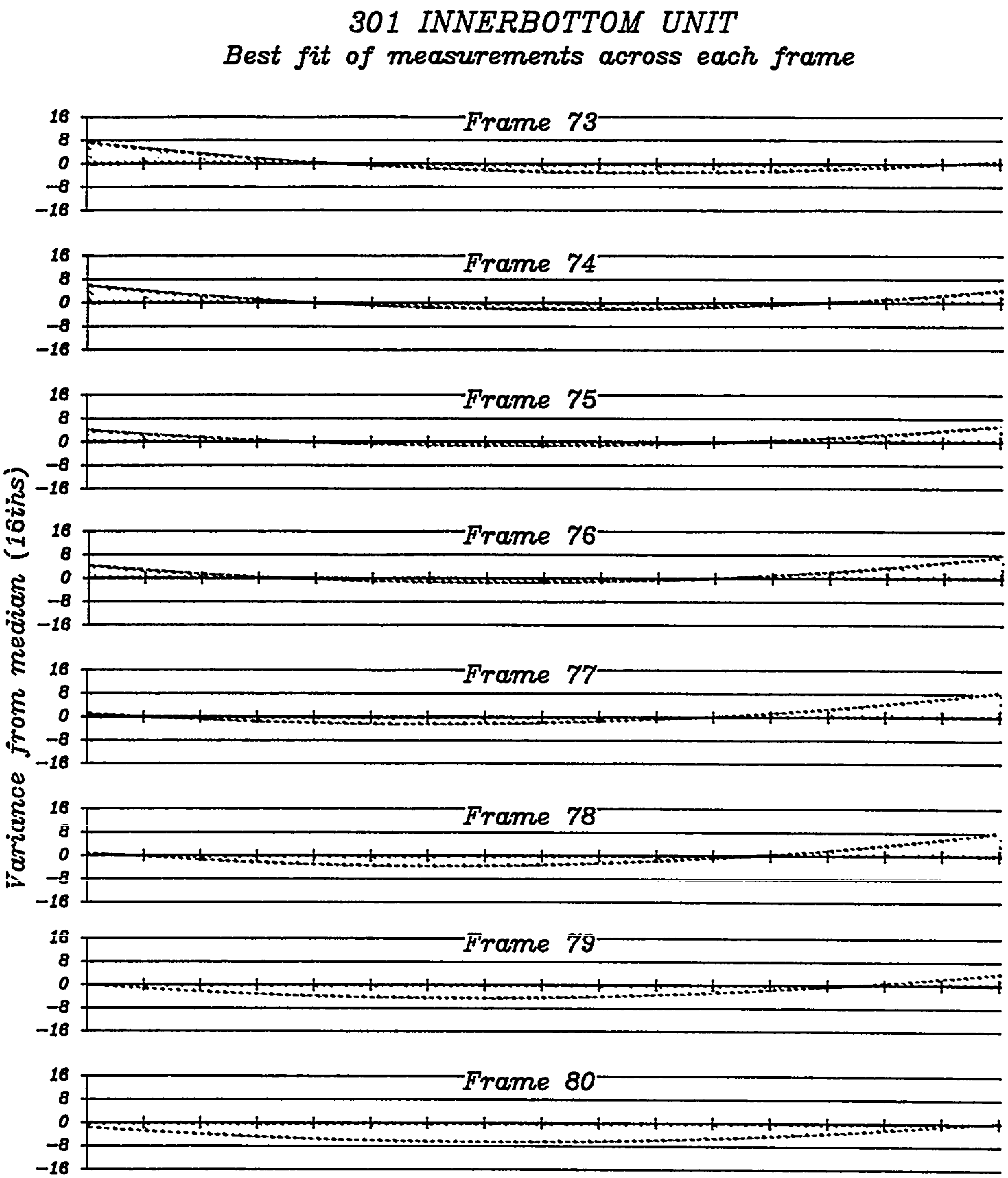


Figure 46. Best fit of variance from median measurements across each frame of the #301 innerbottom unit

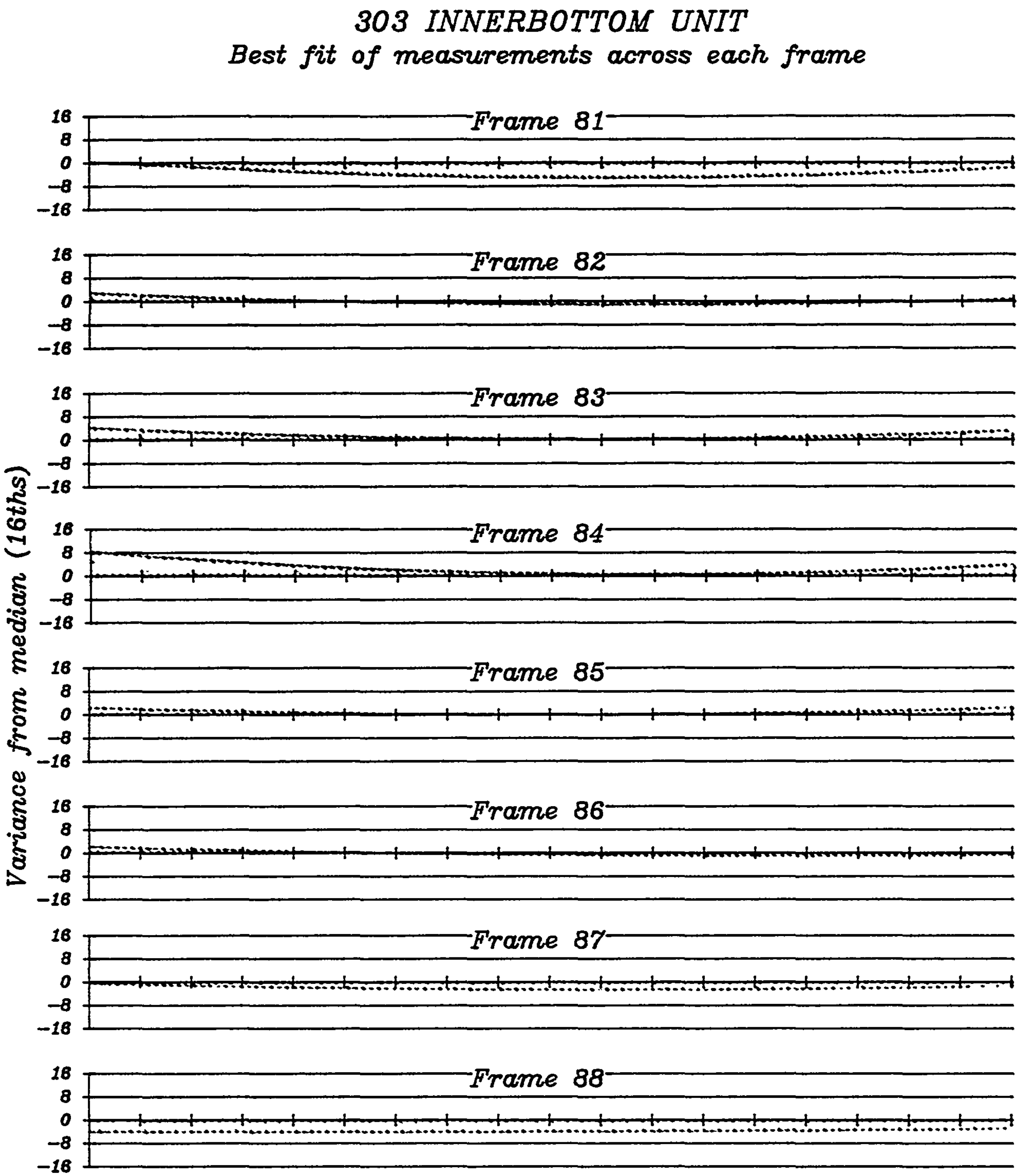


Figure 47. Best fit of variance from median measurements across each frame of the #303 innerbottom unit

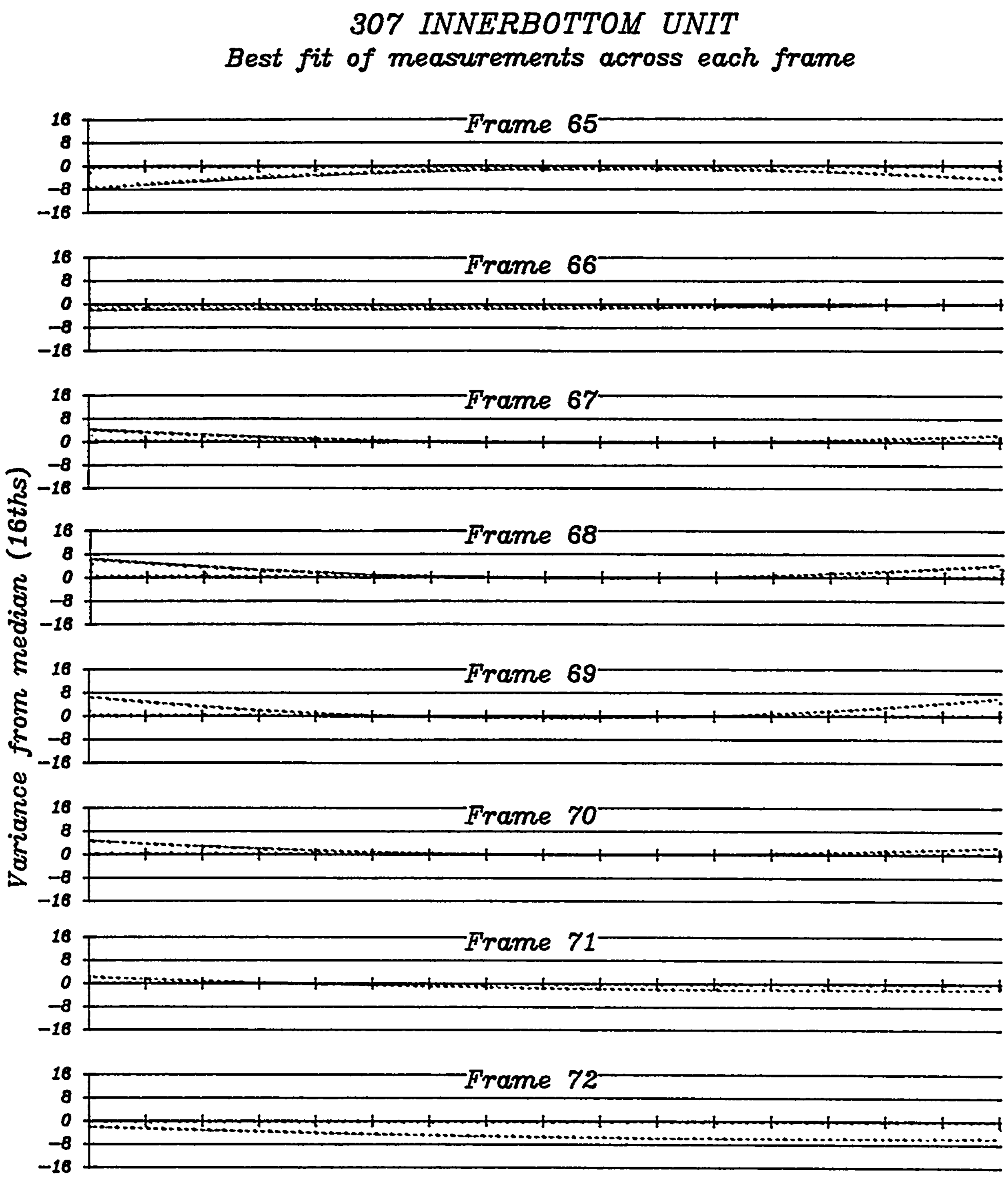


Figure 48. Best fit of variance from median measurements across each frame of the #307 innerbottom unit

Figures 47 and 48 provide the same type of view for the 303 and 307 units respectively. As seen in each of these figures, some small preset reverse bow remains across most frames. Many frames, however, are nearly flat. Only one, frame 65 on the 307 unit, displays a bow in the opposite direction. Consequently, given the consistency of this pattern, a reduction in the 1" preset amount should provide increased levelness in the finished innerbottoms.

As additionally seen in these figures, end frames fore and aft on each unit are generally low to the median plane, and interior frames higher, illustrating the second cause (longitudinal bending). Figures 49, 50 and 51 are a port side elevation view of the mean across each frame of the 301, 303 and 307 units respectively. As shown, a small crown has developed longitudinally. Similar to the distortion transversely, the longitudinal crown can be predicted as a result of bending moments produced from welding. The most probable cause of this bending distortion longitudinally is the effect of transverse shrinkages associated with the shell to floor member fillets, with a lesser contribution from the longitudinal shrinkage of the shell butt welds and the girder to shell fillet welds.

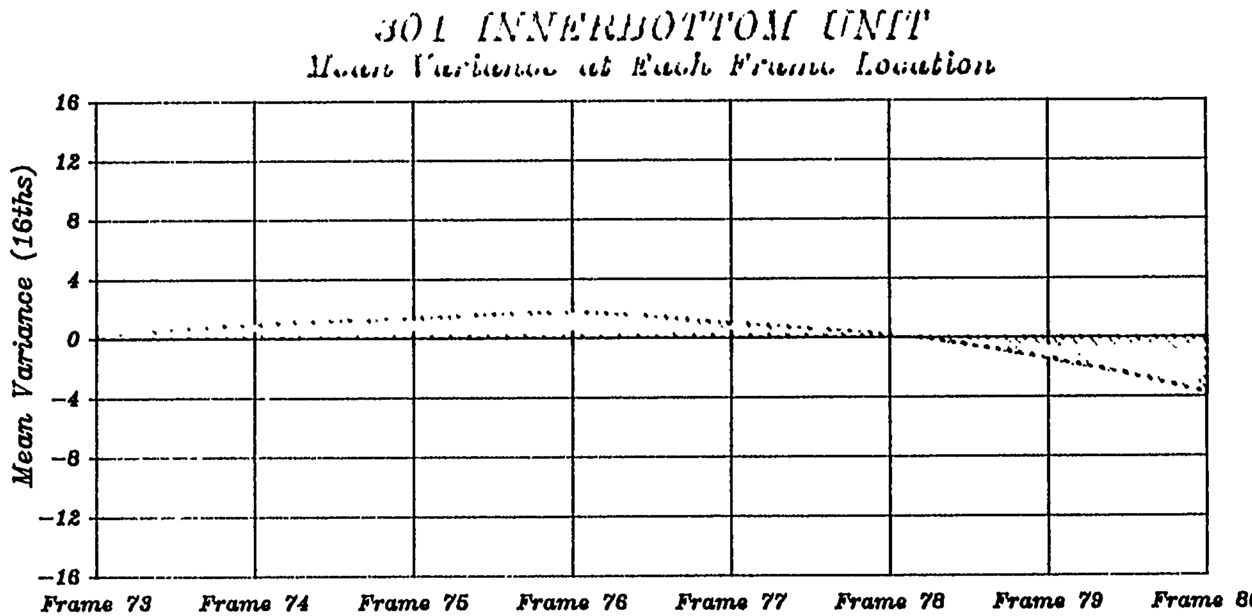


Figure 49. Mean variance from median at each frame of the #301 innerbottom unit

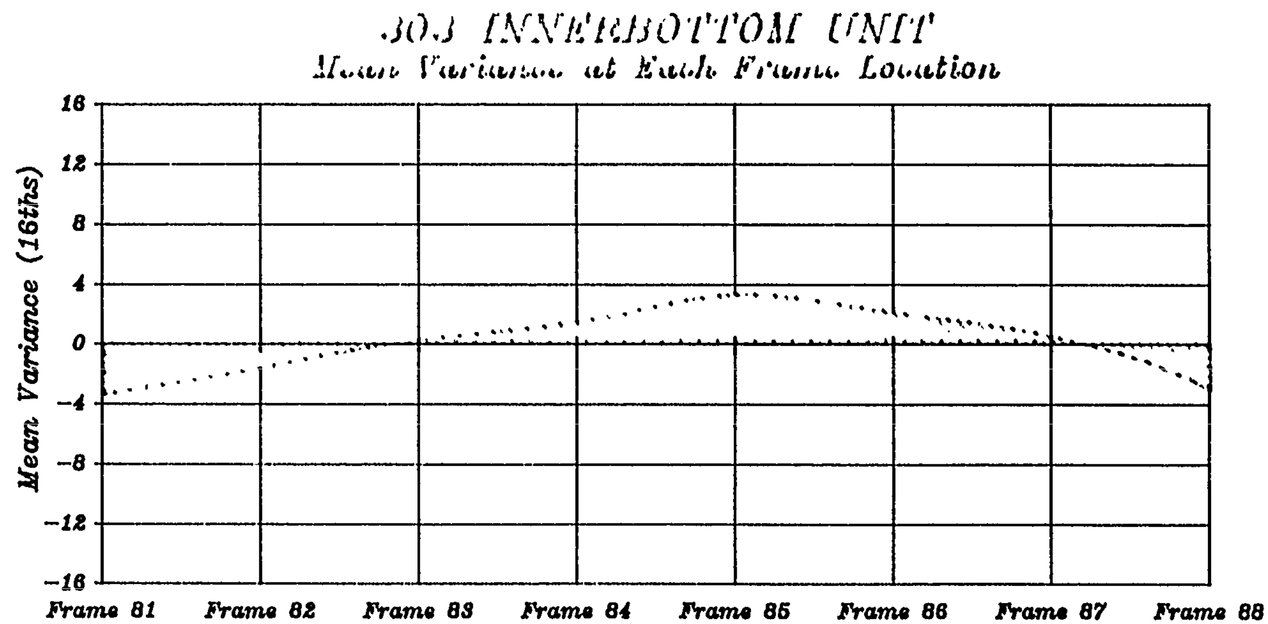


Figure 50. Mean variance from median at each frame of the #303 innerbottom unit

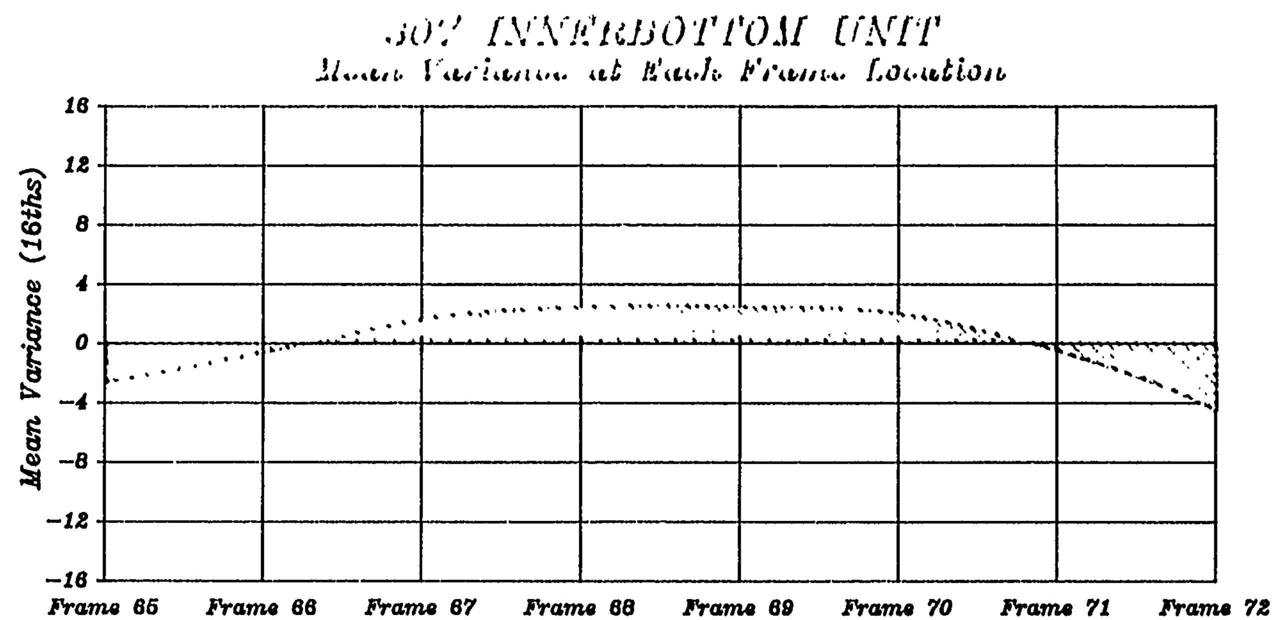


Figure 51. Mean variance from median at each frame of the #307 innerbottom unit

11.0 Backstep and Wandering Weld Sequences

"Weld sequencing" is a term that is often used to describe both the order in which joints in a component are welded, as well as the order in which passes or increments in a single joint are made. The means by which these weld sequences reduce distortion can be generally grouped into one of two categories: (1) those sequences which balance shrinkage forces, and (2) those sequences which add restraint to shrinkage forces.

Balancing of shrinkage forces is generally accomplished (as well as possible) around the neutral axis of the weldment. In a component such as the foundation in Figure 22, joints may be sequenced to produce offsetting bending moments. For a single joint such as the double-vee butt shown in Figure 21, passes on each side of the neutral axis can similarly produce offsetting moments. As a result, net distortion is reduced.

The backstep sequence is a commonly used method for reducing distortion through added restraint to shrinkage forces. As shown in Figure 19, the backstep sequence invulves. stepping though a joint in short individual increments that are opposite in direction to the progress cf the weld. For each increment, restraint is imposed by both its beginning and end locations. As the beginning of an increment cools and solidifies it adds restraint to the remaining increment length. In the same manner. each increment is ended at a previously welded. ralatively rigid location that similarly restrains its shrinkage. Overall reduction in distortion of the joint is obtained accumulatively from sach increment.

The backstep sequence is only useful when welding with manual or semi-automatic processes. This sequence cannot be used economically with fully automatic welding where it negates the speed advantage of the process. In shielded metal arc welding, the length of increments are normally made the welding length of one electrode.

The controlled wandering sequence is a variation of the backstep sequence, particularly useful on longer joints. Figure 52 illustrates the controlled wandering sequence as applied to

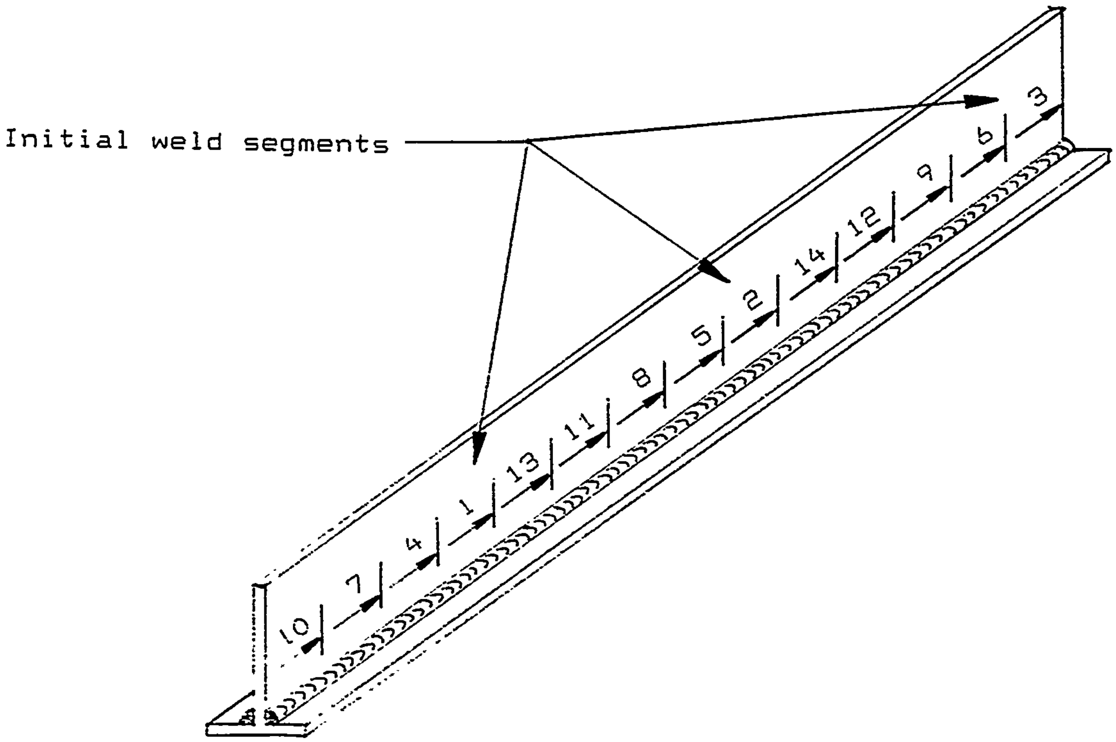


Figure 52. Controlled wandering sequence applied to the fillets of a long, built-up tee section

the fillets of a long, built-up tee section. As shown, a series of three or four short weld segments are placed along the joint at approximately equal spacing. Subsequent welding is then accomplished by backstepping into each of these segments. No more than one or two backstepping increments are accomplished at any single location before moving to the next one.

In addition to providing added restraint to shrinkage at each individual increment as accomplished through the backstepping procedure, the controlled wandering sequence spreads the heat of welding around the joint. Individual increments are allowed to cool prior to adjacent increments being welded.

11.1 Test Method

ln this effort, the extent of distortion reduction using backstep and wandering sequencres was measured. Using each of these sequences, twenty pairs of test plates were flux core butt welded in a single pass. After welding, angular distorhion measurements were taken and then compared to similar measurements on 20 pairs welded in a continuous pass.

Test plates were 18"x6"x0.25" mild steel. Edge preparation of the plates included a 15 degree bevel (providing a 30 degree bevel for the butt) and a 0.063" land.

Pairs of test plates were tacked together along the 12 inch sides at 1 inch from each end. During tacking, plates were clamped firm to prevent distortion from tacking and maintain a level configuration prior to welding. Tacks were made as small a possibls.

During weiding, one test plate in each pair was clamped to a fixture and the other plate left free to distort. Welding was accomplished using the backstep sequence, wandering sequence and cantinuos weld as provided in Figure 53. As shown for the backstep and wandering sequences, plate butts were welded in in six increments, with each increment three inches in length. The backstep sequence was started on the end of the butt. Each succssive increment was made adjacent to and welded in the direction of the previous one. The wandering sequence was started with two separate increments, each located three inches

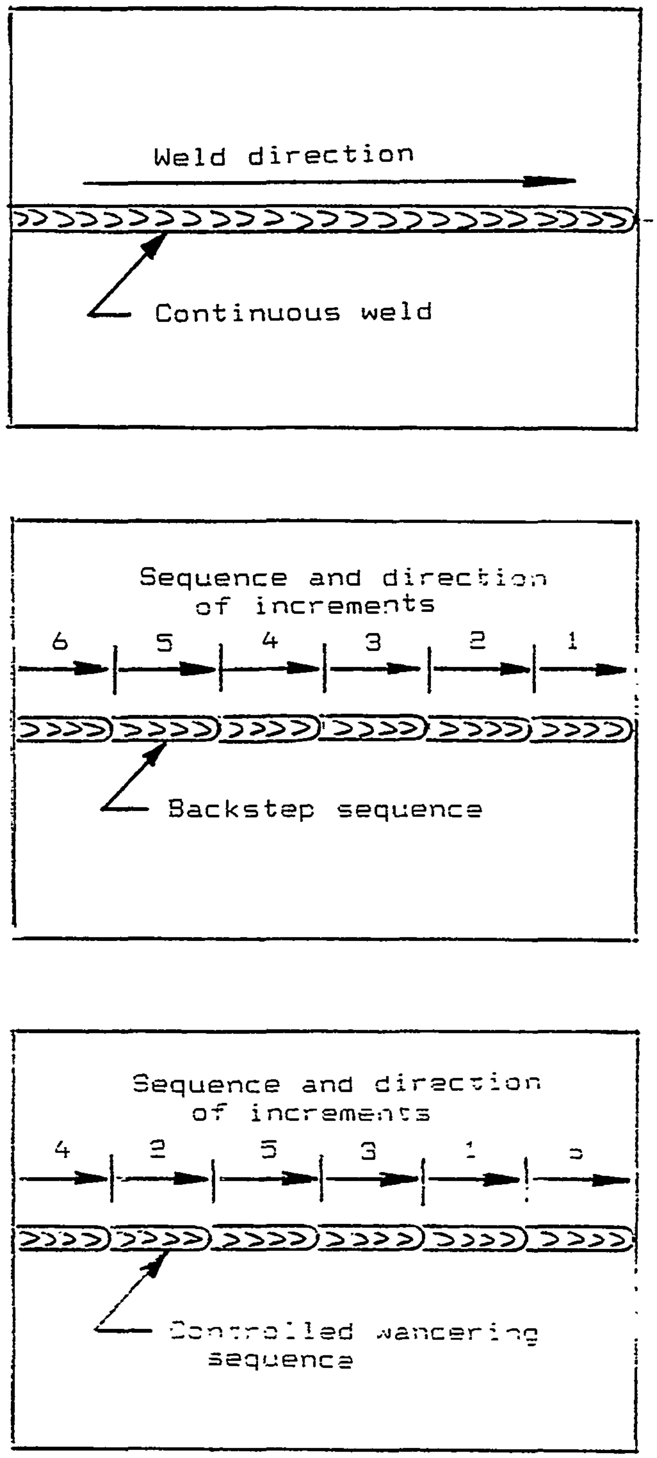


Figure 53. Continuous, backstep and wandering weld sequences used in testing

from the end of the butt. Successive increments filled in the remaining spaces. Welding on each plate was completed prior to starting the next plate.

11.2 Distortion Measurements

After welding, measurements were taken using a dial caliper on each unrestrained plate at three locations along its outer edge (center and one inch from each end) to a plane surface. Angular change (distortion) for each measurement was then calculated.

11.3 Analysis of Measurements

Angular distortion measurements for each of the welding sequences are provided in Table 4. From these measurements, sample mean and standard deviation values are calculated as shown below:

		Backstep Sequence	Continuous Weld	Wandering Sequence
sample mean	=	0.57 deg	1.05 deg	1.33 deg
sample std dev	=	0.50 deg	0.68 deg	0.84 deg
minimum	=	0.00 deg	0.03 deg	0.05 deg
maximum	=	1.81 deg	2.68 deg	3.13 deg

As shown, the backstep sequence provided significantly reduced angular distortion as compared to either the wandering sequence continuous weld. This difference is clearly illustrated in the frequency distiribution of these measurements provided in Figure 54. Specifically, as compared to the icontinuous weld, mean angular distortion through use of the backstep sequence showed a percent reduction of:

$$(1.05 - 0.57)/1.05 = 45.7\ \% \text{ reduction.}$$

To insure that this reduction is not simply a function of the variability associated with the sampling effort, the sample

Table 4. Angular distortion measurements for the test plates welded using backstep sequence, wandering sequence, and a continuous weld

t Weld Sequence	Angular Change (degrees)			Plt Weld # Sequence	Angular Change (degrees)			Plt Weld # Sequence	Angular Change (degrees.		
1 Backstep	1.11	1.42	1.28	21 Wandering	1.24	1.51	1.52	41 Continuous	0.19	0.16	0.43
2 Backstep	0.15	0.27	0.14	22 Wandering	2.16	2.56	2.59	42 Continuous	0.49	1.01	1.31
3 Backstep	0.43	0.27	0.39	23 Wandering	1.33	1.35	1.20	43 Continuous	1.38	1.27	1.25
4 Backstep	0.17	0.17	0.24	24 Wandering	0.76	1.15	1.15	44 Continuous	0.52	0.47	0.63
5 Backstep	0.31	0.14	0.12	25 Wandering	1.66	1.54	2.15	45 Continuous	0.77	1.19	0.75
6 Backstep	1.81	1.63	1.69	26 Wandering	2.37	2.13	2.55	46 Continuous	0.24	0.16	0.47
7 Backstep	1.56	1.48	0.83	27 Wandering	1.42	1.54	0.76	47 Continuous	1.04	0.23	0.54
8 Backstep	0.51	0.33	0.27	28 Wandering	0.28	0.42	0.65	48 Continuous	0.77	1.11	0.71
9 Backstep	0.21	0.39	0.55	29 Wandering	0.71	0.74	0.05	49 Continuous	0.61	[illegible]	0.21
0 Backstep	0.17	0.29	0.34	30 Wandering	1.83	1.71	1.42	50 Continuous	0.47	0.71	0.57
1 Backstep	0.34	0.77	1.08	31 Wandering	0.17	0.23	0.56	51 Continuous	0.22	0.75	[illegible]
2 Backstep	0.75	0.74	1.04	32 Wandering	0.36	0.16	0.45	52 Continuous	1.40	1.70	1.42
3 Backstep	0.86	0.46	0.16	33 Wandering	2.38	2.19	2.48	53 Continuous	0.44	[illegible]	0.65
4 Backstep	0.23	0.02	0.48	34 Wandering	0.42	0.54	0.52	54 Continuous	[illegible]	[illegible]	[illegible]
5 Backstep	0.30	0.12	0.14	35 Wandering	0.57	0.69	0.74	55 Continuous	1.22	2.21	[illegible]
6 Backstep	0.71	0.40	1.16	36 Wandering	1.57	1.55	1.53	56 Continuous	1.50	[illegible]	1.22
7 Backstep	0.21	0.12	0.35	37 Wandering	2.32	2.76	3.12	57 Continuous	2.21	2.32	2.12
8 Backstep	0.05	0.06	1.05	38 Wandering	1.90	2.31	2.54	58 Continuous	2.11	2.22	2.24
9 Backstep	0.22	0.19	0.16	39 Wandering	1.00	0.94	1.27	59 Continuous	1.40	1.27	[illegible]
0 Backstep	1.48	0.95	1.12	40 Wandering	0.50	0.19	0.42	60 Continuous	1.25	1.29	[illegible]

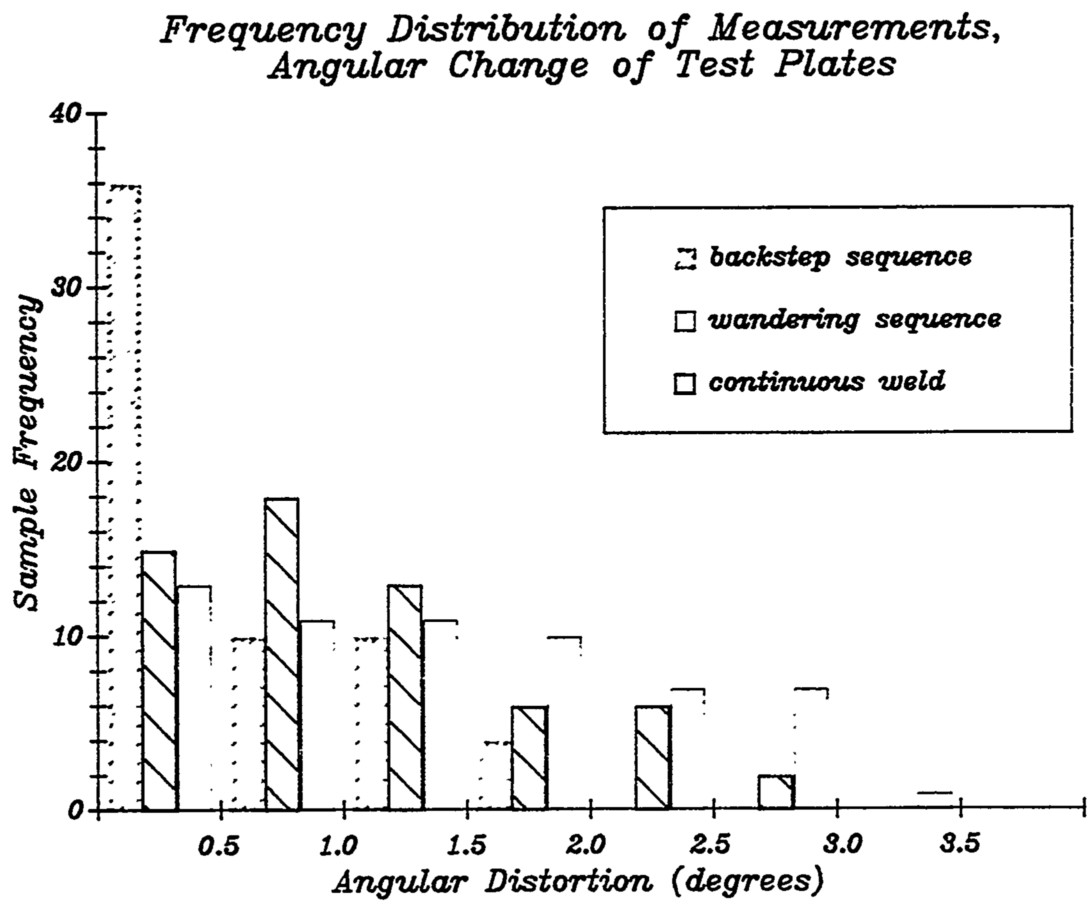


Figure 54. Frequency distribution of angular distortion measurements on test plates welded using a backstep sequence, wandering sequence and a continuous weld

distributions are tested statistically. A test statistic value of z = 4.39 establishes that a mean reduction in distortion through use of the backstep sequence exists at a 95 % level of confidence (see Appendix for explanation of statistical methods).

Thus, it appears that the backstep sequence is an effective method for reducing distortion.

Welds made using the wandering sequence, however, produced quite different results. In this case, angular distortion of the test plates actually showed a mean increase as compared to the plates with continuous welds. This increase in angular distortion through use of the wandering sequence may be calculated as:

$$(1.05 - 1.33)/1.05 = 26.7\ \%\ \text{increase.}$$

Explanation of the this result can be found in the differences in restraint on distortion imposed by each the the weld sequences tested. Figure 55 illustrates these differences.

In a continuous weld, because the length of the weld cannot be laid instantaneously, cooling of the length is not uniform. That part of the weld which is laid first, cools first. In this manner, as each segment of the weld length cools and tends to distort, it is restrained somewhat by the adjcaent, relatively cooler and stronger weld segment. The extent of this restraint is greatest directly adjacent to this cooler segment.

In the backstepped weld, this same restraining effect is observed through each increment. As the beginning of an increment cools and solidifies, it adds restraint to the remaining length of the increment. Additional restraint (beyond that obtained in the continuous weld) is imposed by weiding each increment in the direction of a previously welded location. In this manner, reduced distortion can be expected using a backstep sequence in comparison to a continuous weld.

In the controlled wandering sequence, the initial increments (normally three or four) are purposely laid at equally spaced locations along the juint iength. In the test above, the

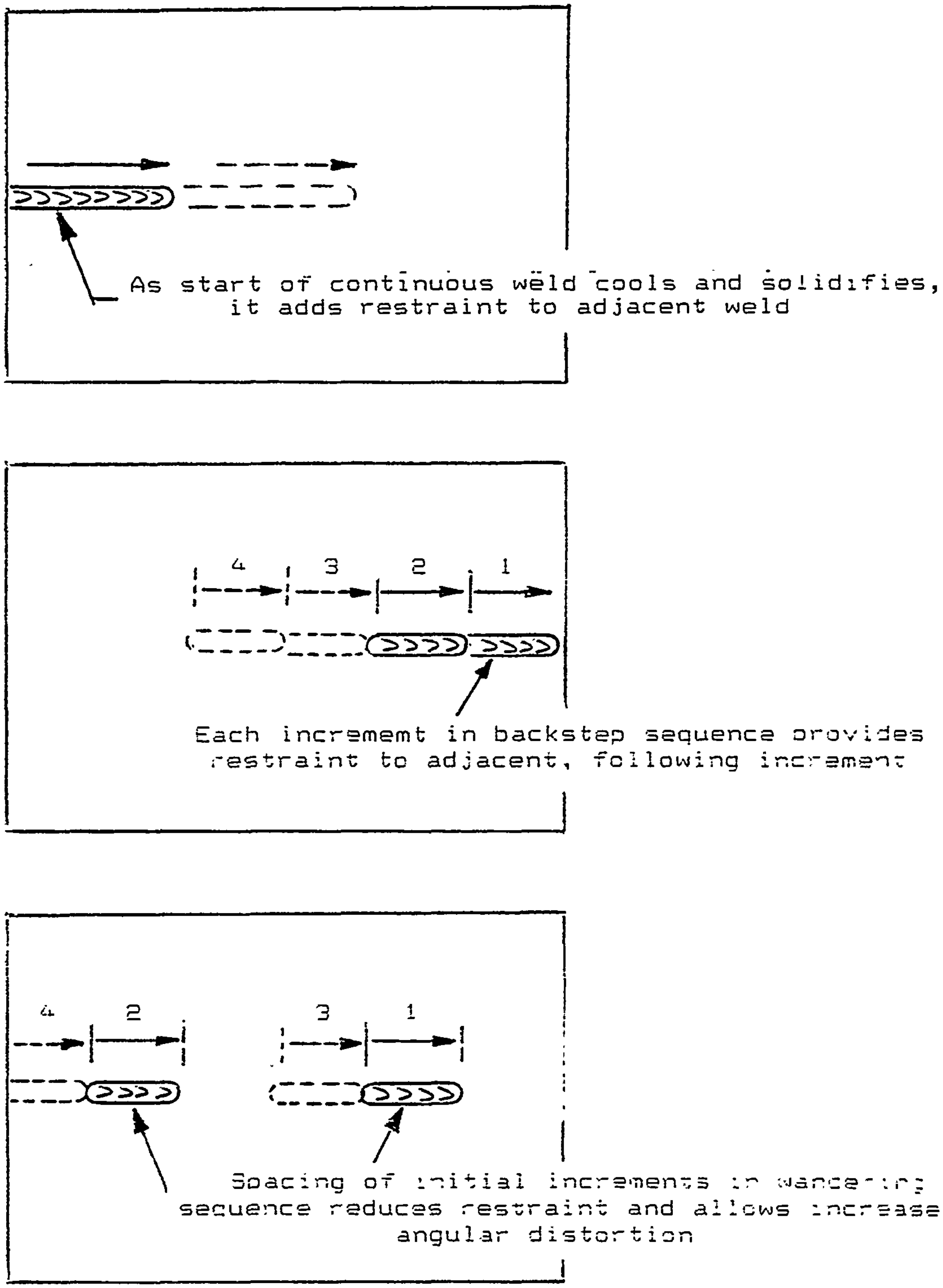


Figure 55. Separation of initial increments in wandering sequence provides less distortion restraint than in backstep sequence or continuous weld in the 18 inch joint tested

first two increments were welded three inches from each end and six inches apart, as shown in Figure 55. Given the separation between these first two increments, less restraint was imposed on distortion as compared to both the continuous and backstep sequences in which all welding was adjacent. As the third and forth increments were applied, some spacing between welded locations still existed, similarly reducing restraint. Thus, in this particular situation, increased angular distortion could be expected using the wandering sequence.

This explanation suggests that the controlled wandering sequence is not preferable to minimizing distortion in shorter joints (such as the 18 inch lengths tested). In longer joints, however, the total weld in the initial increments would be much reduced in comparison to the total joint length. The distortion effect of the these relatively unrestrained increments would be minimal in comparison to the rest of the joint. (Additionally, the effect on distortion of "spreading the heat" through wandering would be much greater. In the reactively short joints tested, the reduction in distortion from this spreading effect could not be properly assessed.

In general, the advantage in using the wandering sequence is not in local restraint (along each backstepped segment) but rather in the restraining effects of one segment upon another. A good example is the circumferential joint, as shown in Figure 56. In this case, starting in one location and backstepping around the whole joint would not be preferable for minimizing distortion. A better alternative would be to use a wandering sequence in which two (or more) initial, evenly spacad increments were established and then backstepping accomplished to these locations. As can be seen. the wandering sequence in this case would provide opposing shrinkage forces across the circumference and significantly increased restraint to distortion.

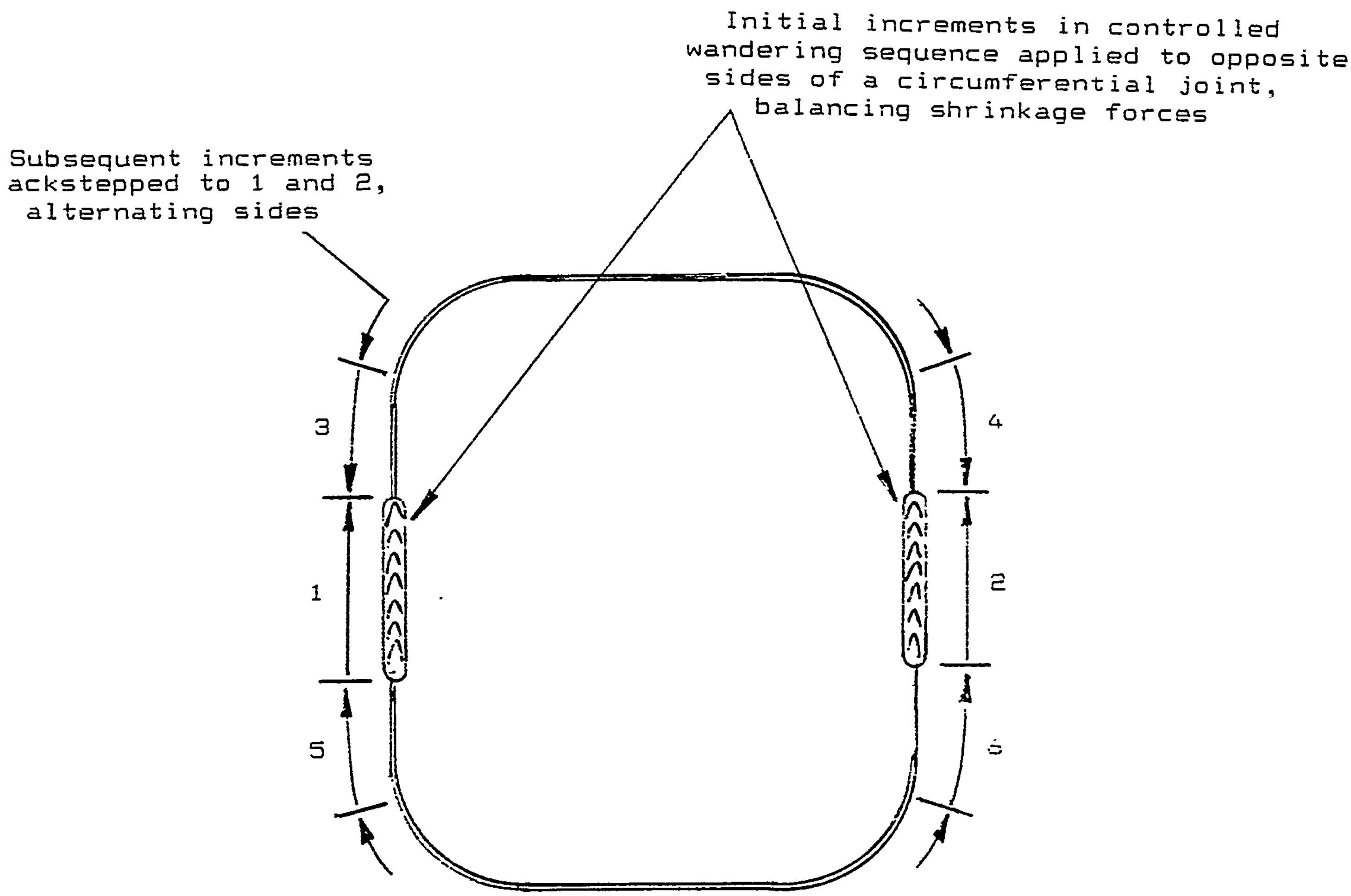


Figure 56. Controlled wandering sequence applied to a circumferential joint

12.0 Preheating of SAW Panel Butt Welds

Distortion in the welding of panel butts is a problem that consistently adds fitting, welding and straightening costs to ship construction. Fitting of frames, longitudinal and bulkheads across distorted panel butts requires increased effort. Additional strongbacking and the use of hydraulic jacks to force proper fitup are often required. On thinner plating, straightening may be employed. In extreme cases, on thicker plating, gouging and rewelding of the panel butts may be required.

Forcing parts into position adds additional strsssses to the structure which may result in immediate distortion in the adjacent plating. When these forces are balanced within the structure, increased distortion often arises later in the construction process when outfitting components are attached. Increased distortion is particularly apparent when structural penetrations, hatches, temporary accesses or other holes in the deck plating are cut.

The added difficulty in fitting parts to distorted panels similarly increases welding costs. When fitup is not accurate, design weld sizes cannot be maintained and overwelding is the result. This additional welding further increases distortion problems.

12.1 preheating Effect on Weld Cooling Rate

Preheating is generally accomplished to reduce the cooling rate of welds. This reduction can provide a variety of beneficial weld qualities, including (ref 23):

- Reduced hardening and loss of ductility
- Reduced formation of cold cracks
- Improved notch toughness
- Reduced residual stress lsvels
- Reduced weld shrinkage and distortion.

The means by which preheating reduces the cooling rate may be explained as a reduction in both the temperature gradient and thermal conductivity of the weld (ref 23). In welding, the fusion of metal necessarily occurs at high temperatures. As solidification of a weld begins, a large thermal gradient exists between the weld and the adjacent base metal which is much cooler. As a result, an exceptionally high cooling rate of the weld and heat affected zone is developed. For some materials, these high cooling rates can promote metallurgical changes that are harmful to the weld quality. For highly restrained joints, either by design or fixturing technique, these high cooling rates can produce stress levels in the weld **that can cause cracking.**

The rate at which a weld cools is dependent upon the difference in temperature between the weld and adjacent base metal. As this temperature gradient decreases, the rate Of cooling aecreases. For a weld without preheating, the metal adjacent to the weld area is at ambient temperature. If this adjacent metal is preheated, then the difference in temperature between it and the weld decreases, thereby reducing the cooling rate of the weld.

another effect of preheating is to reduce the *thermal* conductivity of the weld. Thermsl conductivity is a material property that defines the rate at which a material conducts heat. Metals, for example, generally have much higher thermal conductivity than non-metals and are much better conductors of heat. In the case of iron, its thermal conductivity decreases as its temperature increases. At 1100 F, the thermal conductivity of lron is 50% less than at room temperature (ref 23). As preheating reduces the thermal Conductivity of the weld and heat affected zone, the rate of heat transferer from this area is reduced.

The rate at which a weld solidifies can have a significant impact on its metallurgical structure. Slower cooling rates promote the transformation of the weld and heat affected zone to a favorable microstructure. Specifically, slower cooling rates increase the time spent in the 1330 F to 1600 F temperature range which promotes the transformation of austenite to pearlite

instead of martensite (ref 26). Excessive hardening of the weld and lowering of ductility are avoided. Additionally, slower cooling rates increase the time spent in the 400 F range which allow increased diffusion of hydrogen from the weld and a reduced likelihood of underbead cracking.

Preheating can similarly reduce weld shrinkage. This effect may be explained in the relationship of yield strength to the rate of temperature change. As steel is heated to temperatures above 600 F, an appreciable reduction in yield strength is observed. The rate of this reduction, however, is somewhat dependent on the rate of temperature change. slower rates of temperature change will generally produce lower yield strength values in comparison to faster rates (ref 23). For example, if heated slowly, steel will have a near zero yield strength at approximately 1200 F. If heated quickly, zero yield strength may not be obtained until a temperature as high as 1500 F is reached.

As a weld solidifies and cools, it gradually gains strength. In the inital stages of cooling, the weld has little strength and easily conforms to the changing dimensions of the joint. Plastic flow of the weld is similar to "hot working". Movement of the metal is accomplished with relatively little force and develops minimal stresses internally. As the temperature decreases further, strength of the weld increase and shrinkage stresses develop. Plastic flow becomes similar to "cold working". Reduction in the cooling rate of a weld through Preheating reduces the yield strength in the higher temperature range. In this manner, the amount of hot working of the weld during cooling is increased as comparaed to the amount of cold working and shrinkage stresses are reduced.

Although a reduction in shrinkage stress is known to be an accompanying effect, the use of preheating within industry has been primarily directed at maintaining weld quality. In this respect, the actual use of preheating has been primarily limited to situations governed by welding codes, specifications or other standards: for example, welding in cold weather, welding of castings, and welding of high yield strength materials (HY-80 and HY-100). Preheat temperatures and methods of application have been established to prevent exceeding critical cooling

rates and insuring weld quality. Little use has been made of preheating in situations where weld quality was not of concern. Even less use has been made of preheating strictly as a distortion control method. As a result, proper preheat temperatures and methods of application for minimizing distortion are not well defined.

12.2 Test Method

Preheating was tested as a means of reducing distortion on steel panel butt welds. Preheating was accomplished on panels being constructed in the Panel Shop facility at Ingalls Shipbuilding. The construction sequence in this facility generally follows:

1. Align and fitup panel plating in the shipshape condition. Tacking is normalliy as small as possible, spaced approximately 6 inches apart along each butt length.

2. Attach "run-off tabs" where butts intersect the panel edges. Attach flux backing tape underneath panel butts.

3. Submerge arc weld the root pass of butts. Longitudinal butts are machine welded using a gantry system. Transverse butts are welded using tractor welders. Sequencing is accomplished so that wslding into previously welded locations is avoided.

4. Turn panel to the inverted condition.

5. Submerge arc weld the buttomside pass of butts. Longitudinal and transverse butts are welded again using the gantry and tractor welders, respectively.

Preheating was accomplished on the bottomside pass of the longitudinal butts that are welded using the gantry system. Initial attempts made in preheating the topside root pass encountered problems. In these cases, the preheating applied to the panel prevented the flux backing tape used in the root pass from staying attached to the glating. The tape adhesive melted, causing the tape to fall off the plating in front of the weld.

Preheating effect was still deemed measurable as a function of its impact on the distortion normally caused by the bottom-side pass. This normal impact could be seen in a review of the distortion in the panels completed in the shop at the time. In these cases, a significant majority of the butts were seen to distort angularly in the same direction, toward the molded line side of the plating as shown in Figure 57. From this observation, it could be concluded that the bottomside pass consistently has increased shrinkage over the root pass, since only shrinkage by the bottomside pass could cause angular distortion in this direction (due to its location relative to the neutral axis of the plate). A sampling of angular distortion measurements taken on the butts of non-preheated panels substantiated this effect: 75 % of the locations sampled along the panel edges and 68 % interior to the panels were distorted toward the molded side.

Preheating was accomplished using the oxy-acetylene torch setup provided in Figure 58. As shown, two torches were set in a fixture that was attached to the machine carriage. In this manner, the torches traveled with the welding machine and could be maintained at a constant eight inches in front and seven inches to each side of the weld puddls. Gas flow was constant. Vertical height of the torches (and distance from the weld line, if necessary) could be adjusted to maintain the desired prsheat temperature.

The use of two torches for preheating, one on each side of the weld, was preferable to using a single torch along the weld line. The use of two torches provided much better control of the preheating than would have been afforded with a single torch. This control was particularly necessary when welding plates of different thicknesses. Similar control was necessary when adjusting for variations in ambient temperature, welding speeds, and any movement of the joint during welding. Additionally, any depositing of incomplete combustion from the torches on the weld joint and the rssulting impact on weld quallty was avoided using two torches.

Preheating was accomplished on 62 butts on 10 panels for hulls LHD-1, CG-A6 and CG-68.1 Thinner plated panels were chosen with plate thicknesses ranging primarily between 0.18" and

(1) CG-66 and CG-68 are 9,000 ton U.S. Navy surface combatant ships fabricated at Ingalls Shipbuilding, paseagoula, *MS.*

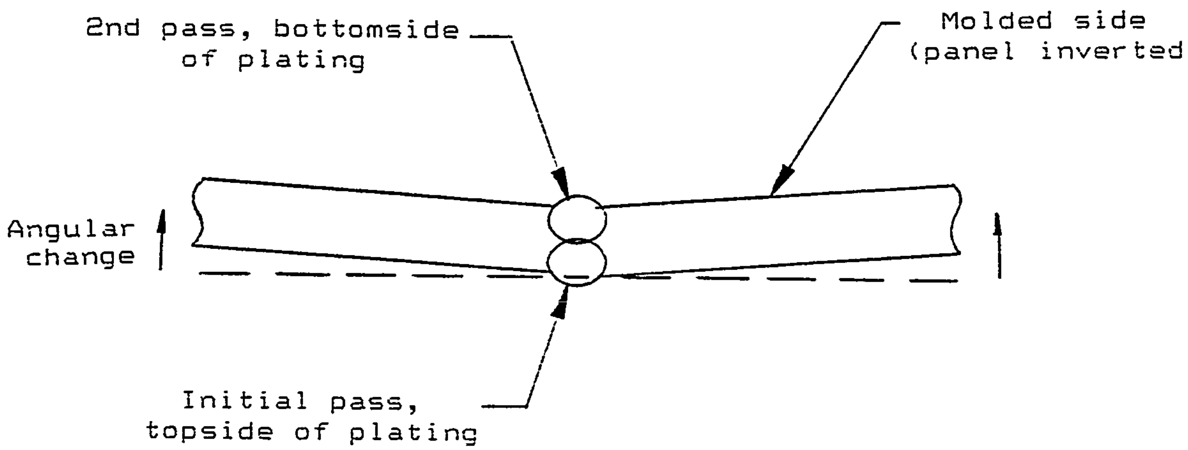


Figure 57. Predominant direction of distortion observed in panel butt welds

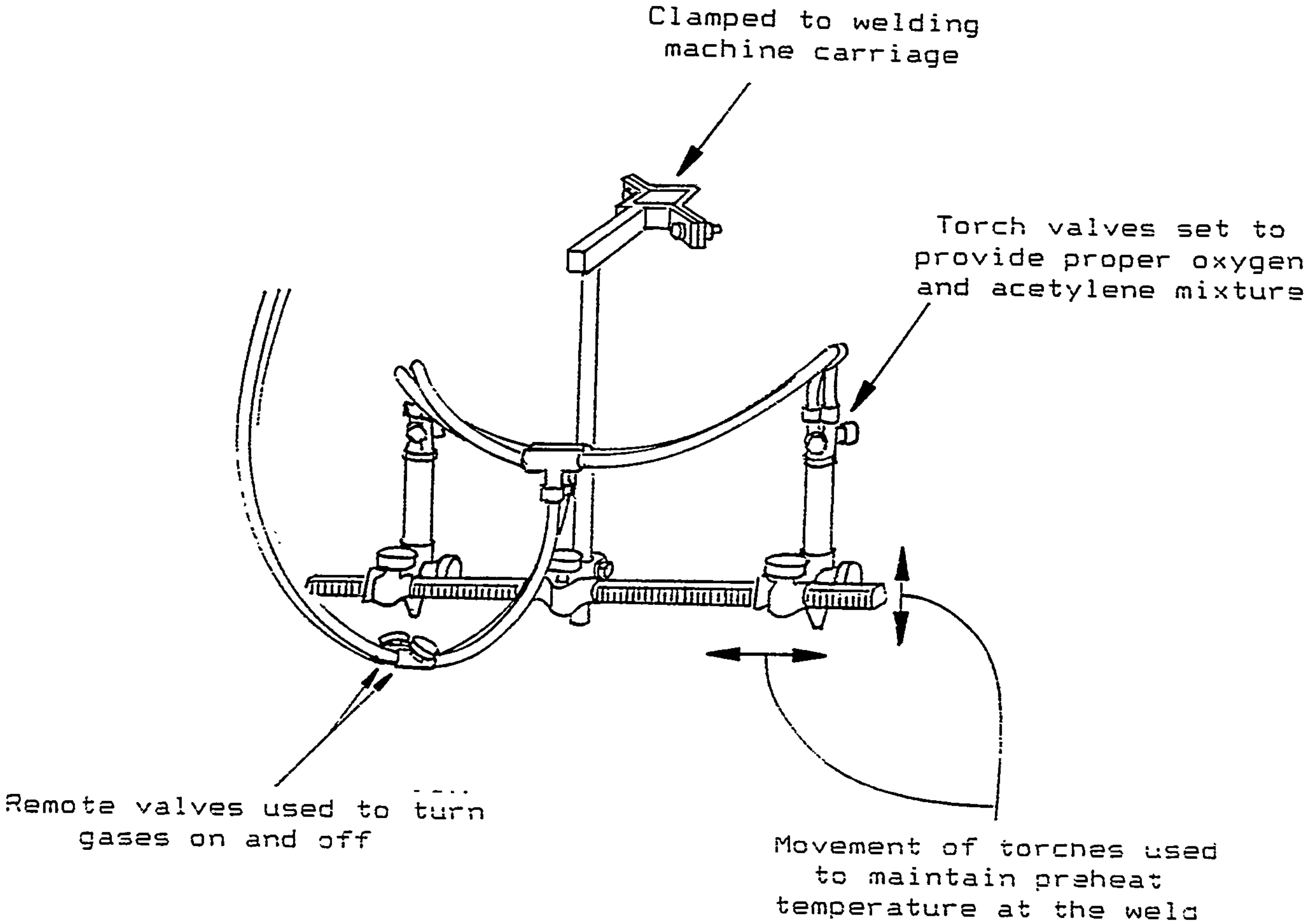
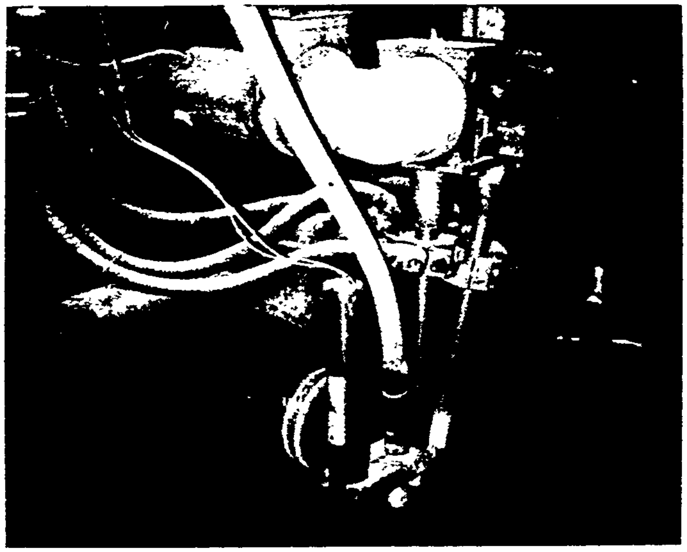
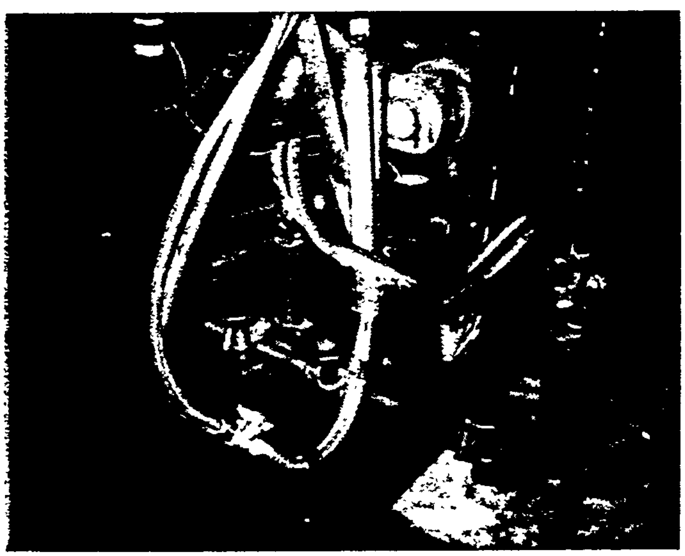


Figure 58. Two torch setup for preheating panel butts, clamped to machine carriage

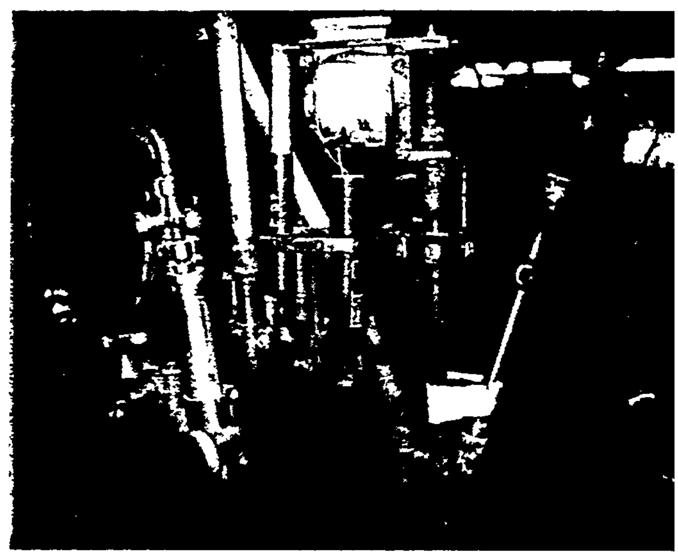


SAW machine without torches

Figure 58. (continued)



With torches (front angle view)



(side view)

0.375" (56 of 62 butts were combinations of plates in this ranges, each of the other 6 butts had 1 plate in this range). Plate materials were primarily Mil–S-24645SH high strength low alloy (HSLA-80) steel and Mil-S-22698B high strength steel (HTS), as shown below,

31 butts -- HSLA-80 to HSLA-80
28 butts -- HTS to HTS
2 butts -- HSLA-80 to HY-80
1 butts -- HSLA-80 to HTS

Panel joints were square with no root gap. Each butt was welded with two passes; a root pass on the topside (panel shipshape) and then a pass on the bottomside (panel inverted) of the weld.

Plating was preheated to within a temperature range of 230 F to "260 F. Temperature measurements were taken using a portable pyrometer. Preheating greater than this range was limited by the 300 F maximum interpass temperature that was specified in welding procedures for HSLA sub-arc wel

Distortion measurements were taken at the panel edges arc then interior at approximately 4 foot intervals. Measurements at the edges and interior were recorded and analyzed separately due to the obviously larger amounts of distortion that occur at the panel edges. Using a dial caliper, distortion was measured as the gap between the weld and a machined straight edge centered across the weld. From these measurements, a nominal angular distortion value was calculated. Distortion direction was denoted as positve (toward molded line) and negative (away from molded line).

92 butts on 18 non-preheated panels were similarly measured provide a norm to which the preheated results could be compared. Thinner plated panels were similarly chosen with 68 of 92 butts being combinations, of 0.188" to 0.375" thicknesses and 23 outts having at least on plate 0.5" thickness or less. Plate materials were also primarily HSLA-80 and HTS, as shown below:

53 butts -- HTS to HTS
28 butts -- HSLA-80 to HSLA-80
8 butts -- Mild Steel to Mild Steel
1 butts -- HTS to Mlild Steel

12.3 Analysis of Measurements

Distortion measurements taken on the preheated panels at both the interior and edges are provided in Table S. Distortion measurements for nonpreheated panels are similarly provided in Table 6. From these measurements, sample mean and standard deviation values are calculated as shown below:

	panel interior		panel edges	
	w/preheat	w/o preheat	w/preheat	w/o preheat
sample mean =	0.28	0.40	0.33	0.81
std. deviation =	1.00	0.88	1.84	1.43
sample size =	251	413	74	113
minimum =	-2.41	-2.11	-3.40	-3.27
maximum =	4.16	3.29	3.76	4.14

As shown, a significant decrease in mean distortion was measured on the preheated panels. Interior to the panels, mean distortion decreased T-rem 0.40 degrees on nonpreheated panels to 0.28 degrees on preheated panels. Along the panel edges, mean distortion simialarly decreased from 0.81 to 0.33 degrees. As a percentage change, these reductions in distortion may be calculated as:

panel interior, (0.40 - o.2a)/o.40 = 50.0 % reduction

panel edges, (o.81 - o.33)/o.81 = 59.3 % reduccion.

To insure that these reductions in mean distortion are not simply a fuinction of the variability associated with the samoling effort, the sample distributions are tested statistically (see Appendix for explanation of statistical methods). Interior to the panel, a test statistic value of z = 1.911 establishes that a mean reduction in distortion exists at a 95 % level of confidence. Along the panel edges, a test statistic value of z = 1.57 rejects a reduction in distortion at this confidence level (z must be greater then 1.645). However, this rejection is very

Table 5. Distortion measurements, interior and edges, on panels with preheat

Panel/ Butt #	Plate 1 Thk	Plate 1 Mat'l	Plate 2 Thk	Plate 2 Mat'l	Angular Distortion (degrees) Panel Edges		Panel Interior						
A1	0.250	HTS	0.250	HTS	2.33	-2.63	0.67	0.40	-0.38	-0.30	0.22	-0.27	-1.25
A2	0.250	HTS	0.375	HTS	0.05	0.37	0.23	-0.38	-0.25	-0.41	1.35	-0.13	0.69
A3	0.250	HTS	0.250	HTS	2.68	2.65	2.40	1.15	0.90	-0.06	0.62	0.23	1.33
A4	0.375	HTS	0.375	HTS	0.31	1.32	-0.29	-0.14	-0.12	-0.14	0.15	0.25	0.22
B1	0.250	HTS	0.250	HTS	-1.36	1.61	0.72	-0.58	0.31	2.13	0.47	0.25	1.37
B2	0.250	HTS	0.250	HTS	0.73	2.28	1.26	-0.25	-0.14	2.10	1.70	0.86	0.38
B3	0.250	HTS	0.313	HTS	2.13		1.79	1.33	0.46				
B4	0.313	HTS	0.250	HTS	0.97		1.37	0.66	-0.11				
B5	0.250	HTS	0.313	HTS	1.25		-0.30	-0.49	-0.36				
B6	0.250	HTS	0.250	HTS	3.76	1.91	0.11	-0.52	-0.38	1.15	0.51	-0.05	0.30
B7	0.250	HTS	0.250	HTS	0.36		1.12	0.50	0.43	2.02			
C1	0.250	HTS	0.250	HTS	1.36	-2.07	0.18	-0.17	-0.10	-0.25	0.06	-0.35	-0.13
C2	0.250	HTS	0.250	HTS	-1.78	-2.96	-0.06	-0.71	-0.46	-1.59	-0.60	0.33	0.30
C3	0.250	HTS	0.250	HTS	-2.12	1.46	-0.57	-0.79	2.70	-0.76	-0.37	0.31	0.24
C4	0.250	HTS	0.250	HTS	1.35		0.79	-1.09	-0.71	0.41	-0.07		
D1	0.250	HTS	0.250	HTS	-3.08	-0.10	-0.16	-0.13	1.27	0.92	-0.09	0.45	0.53
D2	0.250	HTS	0.250	HTS	-0.30	-1.91	-0.46	-0.49	-0.37	-0.46	-0.12	-0.17	[illegible]
D3	0.250	HTS	0.250	HTS	0.31	-1.97	0.09	-0.40	0.37	0.79	-0.14	0.77	-0.13
E1	0.250	HTS	0.250	HTS	-2.74		-0.20	0.08	0.85	0.72	-0.64	-0.55	
E2	0.250	HTS	0.250	HTS	1.31	0.71	0.63	0.35	0.51	0.72	0.29	0.50	1.37
E3	0.250	HTS	0.250	HTS	1.49	1.60	0.54	1.24	0.05	0.24	0.54	0.26	[illegible]
E4	0.250	HTS	0.250	HTS	-1.59	-1.16	0.06	-1.50	0.55	1.33	0.36	0.59	2.13
E5	0.250	HTS	0.250	HTS	-1.44	-0.75	0.49	0.79	0.52	0.71	1.20	-0.60	[illegible]
F1	0.281	HTS	0.281	HTS	-0.91	1.48	-0.73	0.37	-1.73	-1.25	-1.59	-0.65	
F2	0.281	HTS	0.281	HTS	2.56	-0.32	-0.59	-0.56	1.76	0.37	1.58	[illegible]	
F3	0.281	HTS	0.281	HTS	2.10	1.51	0.73	[illegible]	[illegible]	[illegible]	-0.42	[illegible]	
F4	0.281	HTS	0.281	HTS	-2.59	-2.37	-1.33	-1.46	-1.15	-1.59	[illegible]	[illegible]	
F5	0.281	HTS	0.281	HTS	[illegible]	1.26	-0.47	-0.12	[illegible]	[illegible]	2.31	[illegible]	
G1	0.188	HSLA	0.188	HSLA	1.05		-0.15	[illegible]					
G2	0.188	HSLA	0.188	HSLA	-0.15		0.56						
G3	0.188	HSLA	0.188	HSLA			[illegible]						
G4	0.188	HSLA	0.188	HSLA	-0.24		0.52	-1.51					
G5	0.250	HSLA	0.188	HSLA	2.20	2.21	1.21	[illegible]	1.35	1.33			
G6	0.188	HSLA	0.313	HSLA			1.73						
G7	0.188	HSLA	0.188	HSLA			1.26						
G8	0.188	HSLA	[illegible]	HSLA	-0.73		-1.25						
G9	0.313	HSLA	0.188	HSLA			0.82						
H1	0.313	HSLA	0.313	HSLA			1.00						
H2	0.188	HSLA	0.250	HSLA	2.65		[illegible]	0.54	[illegible]	[illegible]			
H3	0.188	HSLA	0.188	HSLA	2.14		-0.40	1.21					
I1	[illegible]	HSLA	[illegible]	HSLA	[illegible]								

Table 5. (continued)

Panel/ Butt #	Plate 1 Thk	Plate 1 Mat'l	Plate 2 Thk	Plate 2 Mat'l	Angular Distortion (degrees) Panel Edges	Panel Interior				
I2	0.438	HSLA	0.188	HSLA		2.64				
I3	0.750	HSLA	0.188	HSLA	-1.16					
I4	0.250	HSLA	0.188	HSLA		-0.62	-0.89			
I5	0.188	HSLA	0.188	HSLA		-2.07	0.46	-0.51		
I6	0.219	HSLA	0.219	HSLA	1.36					
I7	0.188	HSLA	0.188	HSLA	-3.08	-2.11	2.68	0.06	[illegible]	[illegible]
I8	0.219	HSLA	0.219	HSLA	3.29					
I9	0.250	HSLA	0.219	HSLA	1.45	0.08				
I10	0.188	HSLA	0.188	HSLA	2.71	2.81	0.26	-0.21	1.25	3.67
I11	0.188	HSLA	0.188	HSLA	-3.40	0.36	-0.60	-0.72	0.13	-1.22
I12	0.188	HSLA	0.188	HSLA	1.02	4.16	0.11	0.05	1.33	[illegible]
J1	0.188	HSLA	0.188	HSLA	2.78	-0.02	1.04			
J2	0.250	HSLA	0.188	HSLA	-1.03	2.44	0.01	1.74	-2.41	1.25
J3	0.188	HSLA	0.250	HSLA		-0.45	0.02			
J4	0.188	HSLA	0.188	HSLA	-1.37	-1.67	0.25			
J5	0.188	HSLA	0.188	HSLA	-1.66	-1.07	-1.49	-1.25	[illegible]	
K1	0.375	HY80	0.375	HSLA	-0.23	[illegible]	[illegible]			
K2	0.438	HSLA	0.375	HSLA	1.27	[illegible]	-2.40	[illegible]		
K3	0.375	HY80	0.375	HSLA		0.25	-0.42	[illegible]	[illegible]	
K4	0.375	HSLA	0.750	HSLA		-0.46	0.25	[illegible]	1.55	
K5	0.375	HSLA	0.750	HSLA	0.42	-0.57	-0.79			

Table 6. Distortion measurements, interior and edges, on panels without preheat

Panel/ Butt #	Plate 1 Thk	Plate 1 Mat'l	Plate 2 Thk	Plate 2 Mat'l	Angular Distortion (degrees) Panel Edges		Panel Interior						
A1	0.313	MILD	0.313	MILD	-0.26		0.36	0.67	-0.16	1.36			
A2	0.313	MILD	0.313	MILD	0.62	0.72	1.29	0.79	-0.21	0.29	0.57	-0.39	0.45
A3	0.250	MILD	0.313	MILD	1.62	0.80	1.06	-0.92	-1.43	0.87	0.89	2.14	1.45
B1	0.250	HTS	0.375	MILD	-1.55	-0.29	-0.64	-1.09	-0.42	-0.45	-0.05		
B2	0.375	MILD	0.375	MILD	-0.26		1.08	0.49	1.13	0.53			
B3	0.375	MILD	0.375	MILD	0.94	1.04	0.60	0.73	0.87	0.93	0.34		
B4	0.375	MILD	0.375	MILD	0.13	-0.61	0.90	0.37	0.54	-0.21	0.43		
B5	0.375	MILD	0.375	MILD	-0.94	2.54	0.64	0.52	0.37	0.77	0.07		
C1	0.438	HTS	0.625	HTS	1.42		0.20	0.55					
C2	0.438	HTS	0.438	HTS	0.94	-0.23	0.24	0.36	-0.26	0.24			
C3	0.250	HTS	0.375	HTS	-0.61		1.11	-0.29					
C4	0.500	HTS	0.375	HTS	0.92		-0.49	0.49					
C5	0.438	HTS	0.375	HTS	-0.12		0.23	0.77					
C6	0.375	HTS	0.438	HTS	1.63	0.71	0.38	0.27	-0.09	0.52			
C7	0.375	HTS	0.375	HTS	0.76	0.87	0.77	0.18	0.21	0.50			
C8	0.375	MILD	0.375	MILD	1.28		1.69	1.33	0.91				
D1	0.625	HTS	0.500	HTS	1.79	3.03	1.60	1.33	1.76	1.59	0.83	1.07	1.84
D2	0.500	HTS	0.500	HTS	1.10	2.23	0.68	0.71	0.85	0.48	0.78	0.74	1.40
E1	0.375	HTS	0.375	HTS	0.44	1.72	0.18	0.58	0.32	0.15	0.62	0.54	1.26
E2	0.375	HTS	0.375	HTS	0.37	1.47	0.53	0.79	0.45	0.45	0.39	1.17	
E3	0.375	HTS	0.375	HTS	-0.25	1.74	0.27	1.01	0.57	0.54	0.63	0.84	2.24
E4	0.375	HTS	0.375	HTS	-1.57	2.35	0.22	1.28	-0.32	0.66	0.57	0.61	1.65
F1	0.500	HTS	0.500	HTS	1.12	2.05	1.20	1.37	0.96	0.95	1.32	0.92	1.06
F2	0.500	HTS	0.500	HTS	0.47		0.64	1.18	1.28	1.50			
F3	0.500	HTS	0.500	HTS	0.74	1.39	0.47	0.38	0.76	1.09	1.03	0.89	1.00
F4	0.500	HTS	0.500	HTS	0.87		0.50	0.13	0.02	0.47	1.31	0.28	
G1	0.250	HTS	0.250	HTS	2.38		1.31	1.48					
G2	0.250	HTS	0.250	HTS	2.02		0.51	-0.92	-0.33	-0.88	-0.76	-0.07	-0.55
G3	0.250	HTS	0.250	HTS	1.34		-0.83	-0.58	-0.12	-1.10	-0.60	-0.43	-0.26
G4	0.250	HTS	0.250	HTS	1.79		1.03	1.07	0.66	1.39	-0.34	0.70	
H1	0.250	HTS	0.250	HTS	-2.73		0.50	-0.43	0.83	-0.09	1.22	-0.93	0.96
H2	0.250	HTS	0.250	HTS	2.66		0.63	-1.13	-0.61	1.57	0.71	-1.05	0.39
H3	0.250	HTS	0.250	HTS	1.78		1.02	0.37	2.17				
H4	0.250	HTS	0.250	HTS	2.17		-0.47	-0.12	1.07	-0.57	0.66	-1.39	2.53
H5	0.250	HTS	0.250	HTS	1.06		0.07	-0.76	-0.19	-0.41	-0.29	1.25	-0.30
I1	0.250	HTS	0.250	HTS	-0.49		0.32	0.80	-1.11	-0.71			
I2	0.250	HTS	0.250	HTS	2.68		1.05	1.03	-0.30	0.32	-0.20	-0.33	1.53
I3	0.250	HTS	0.250	HTS	1.22		0.86	-0.26	-0.11	-0.53	-0.34	-1.31	-0.22
J1	0.250	HTS	0.250	HTS	1.94		1.57	-0.35	-0.60	-0.09	0.72		
J2	0.250	HTS	0.250	HTS	0.58	1.51	-0.20	0.22	0.46	0.11	-0.77	0.08	0.28
K1	0.250	HTS	0.250	HTS	-2.71		2.35	-0.28	0.59	-0.87	-0.48	1.53	-1.15
K2	0.250	HTS	0.250	HTS	-2.32	1.23	-1.15	-0.62	-0.21	0.35	-0.92	0.33	-1.57
K3	0.250	HTS	0.250	HTS	-0.45	0.97	0.65	0.59	1.64	0.73	0.51	1.20	0.52
K4	0.250	HTS	0.250	HTS	-0.17		1.37	1.12	1.29				
K5	0.250	HTS	0.250	HTS	1.46	1.23	0.60	1.35	1.15	1.14	-0.21	-0.15	0.24
L1	0.500	HTS	0.500	HTS	0.06	-0.03	0.38	0.79	0.18	0.61			
L2	0.500	HTS	0.500	HTS	0.31	0.72	0.55	0.16	0.28	0.42	0.58	1.08	

Table 6. (continued)

Panel/ Butt #	Plate 1 Thk	Plate 1 Mat'l	Plate 2 Thk	Plate 2 Mat'l	Angular Distortion (degrees) Panel Edges		Panel Interior						
L3	0.500	HTS	0.500	HTS	0.17	0.89	-0.16	0.84	0.31	-0.52	0.88	-0.23	
M1	0.219	HSLA	0.250	HSLA	0.81		-0.46	0.66	-0.29	1.03			
M2	0.219	HSLA	0.219	HSLA	1.84	0.61	0.44	-0.31	-0.93	-0.42	0.94		
M3	0.219	HSLA	0.219	HSLA	-2.34	-0.28	-0.79	-1.69	-0.21	-0.32	-0.92		
M4	0.219	HSLA	0.219	HSLA	-2.03		-1.62	-0.61	-0.37	-0.70	1.94		
M5	0.219	HSLA	0.219	HSLA	-1.81		2.21	-1.72	-1.48	-1.17			
M6	0.219	HSLA	0.219	HSLA	0.93		3.29	-0.21	-0.10	0.81			
M7	0.219	HSLA	0.250	HSLA	0.68		0.95						
M8	0.250	HSLA	0.219	HSLA	3.30	0.73	0.72	-0.48	-0.44	-0.92	0.53		
M9	0.250	HSLA	0.250	HSLA	1.00		-0.76						
M10	0.219	HSLA	0.219	HSLA	1.03	1.79	1.52	-1.20	1.02	-0.91	1.83		
N1	0.219	HSLA	0.250	HSLA	-2.25								
N2	0.188	HSLA	0.250	HSLA	2.04		2.69	-0.85	-0.32	-0.87	0.41		
O1	0.188	HSLA	0.188	HSLA	3.09		1.58	0.42	0.43				
O2	0.188	HSLA	0.188	HSLA	-3.27		-2.11	1.17	1.61				
O3	0.188	HSLA	0.188	HSLA	2.96		3.12	0.47	1.43				
O4	0.188	HSLA	0.188	HSLA	2.55		1.02	0.36	0.21				
O5	0.250	HTS	0.250	HTS			-1.32	-0.50	0.55				
O6	0.188	HSLA	0.250	HSLA	2.67		1.11	-1.98	-0.28				
O	0.250	HTS	0.250	HTS			0.45	-0.94	1.23				
O7	0.250	HTS	0.250	HTS	0.56		-1.02	-0.44	1.77				
O8	0.188	HSLA	0.188	HSLA	4.14		2.28	2.15	-0.34				
O9	0.250	HTS	0.250	HTS			1.34	0.58	1.39				
O10	0.250	HSLA	0.188	HSLA	2.77		2.75	-0.80	-0.42				
O11	0.250	HTS	0.250	HTS			-0.80	-0.34	-0.34				
P1	0.250	HTS	0.250	HSLA	0.83		0.51	0.58					
P2	0.250	HTS	0.250	HTS	1.36		0.78	1.09					
P3	0.188	HSLA	0.188	HSLA	2.05		1.87	2.05	0.66	0.66			
P4	0.188	HSLA	0.188	HSLA	-1.50		0.59	1.50	-1.73	2.22			
P5	0.250	HSLA	0.188	HSLA			1.64						
P6	0.438	HSLA	0.438	HSLA	-0.78		2.12	0.99					
P7	0.188	HSLA	0.188	HSLA			1.42						
P8	0.188	HSLA	0.250	HSLA	3.46		0.71	-0.33	-0.34	0.08			
P9	0.250	HTS	0.250	HTS	1.11		1.37	1.42					
P10	0.438	HSLA	0.188	HSLA	-1.06		-1.29	-0.46					
P11	0.250	HSLA	0.250	HTS	-0.64		-0.13	-0.38					
P12	0.250	HTS	0.250	HTS	1.23		0.41	0.71					
Q1	0.500	HTS	0.500	HTS	1.58		0.92	-0.23	-0.41	-0.06			
Q2	0.500	HTS	0.562	HTS	3.12	0.63	0.23	-0.09	0.64	1.21	0.27	0.71	0.85
Q3	0.500	HTS	0.500	HTS	-0.72		0.62	0.42	0.11	-0.12			
Q4	0.562	HTS	0.500	HTS	0.87		0.47	0.09	0.83	0.64	0.24	-0.25	0.48
Q5	0.500	HTS	0.500	HTS	0.96	1.02	0.25	0.69	0.61	0.93	0.77	0.37	
Q6	0.562	HTS	0.562	HTS	3.59	0.39	0.06	0.05	0.54	0.71	0.42	0.76	1.38
R1	0.375	HSLA	0.750	HSLA	-0.64	1.61	0.32	0.43	-0.25	-0.56	0.21	0.72	1.51
R2	0.438	HSLA	0.375	HSLA	1.21		-0.29	0.50	2.70				

slight in that acceptance could be obtained at a 94.2 % level of confidence. Thus, it can be safely concluded that a reduction in mean distortion of the panel butts both interior and along the edges was induced through the use of preheating.

However, improvement in panel distortion cannot simply be evaluated through the change in mean values. These reductions in mean distortion can be misleading. Further examination must include the variability of the sample measurements.

As shown in the sample summary values above, although a reduction in mean distortion was observed in the preheated panels, an increase was observed in the variability (standard deviation) of the measurements. Interior to the panel, standard deviation increased from 0.88 degrees on nonprsheated panels to 1.00 degrees on preheated panels. Along the panel edges, standard deviation increased from 1.43 to 1.84 degrees. As a percentage increase, these may be calculated as:

panel interior, (0.88 - 1.00)/0.88 = 13.6 % increase

panel edges, (1.43 - 1.84)/l.43 = 29.7 % increase.

The result of this increase in variability is to negate the improvement that was observed in mean distortion. In ether words, just as many sample locations had "large" distortion values with preheating as without it. Interior to the panel, this comparison may be seen in the frequency distribution of the distortion measurements provided in Figure 59. Along the panel edges, a similar comparison is provided in Figure 60.

in another form, this comparison of preheated and non-preheated results may be shown as the percentage of sample locations outside ranges of distortion:

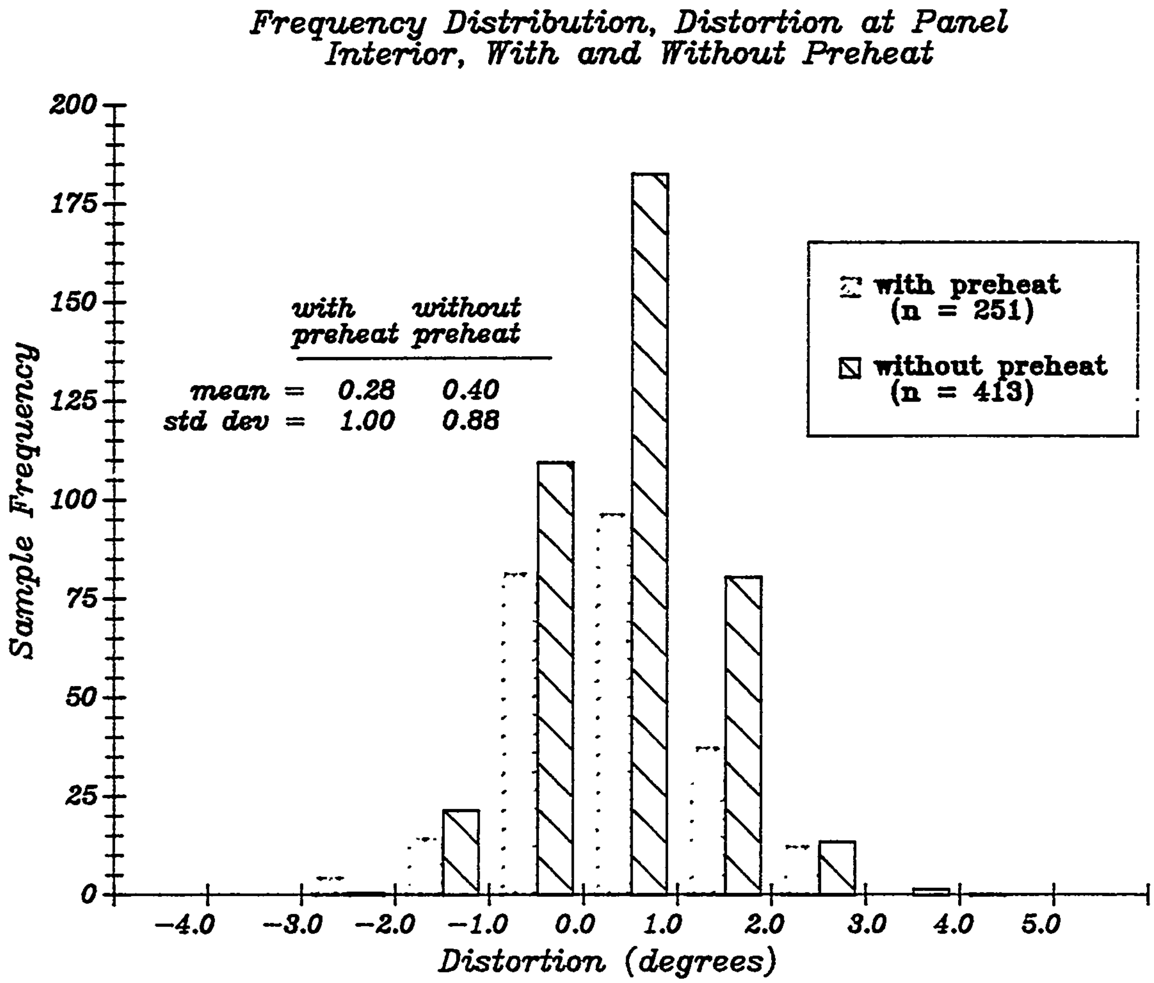


Figure 59. Frequency distribution of distortion measurements interior for panels with and without preheat

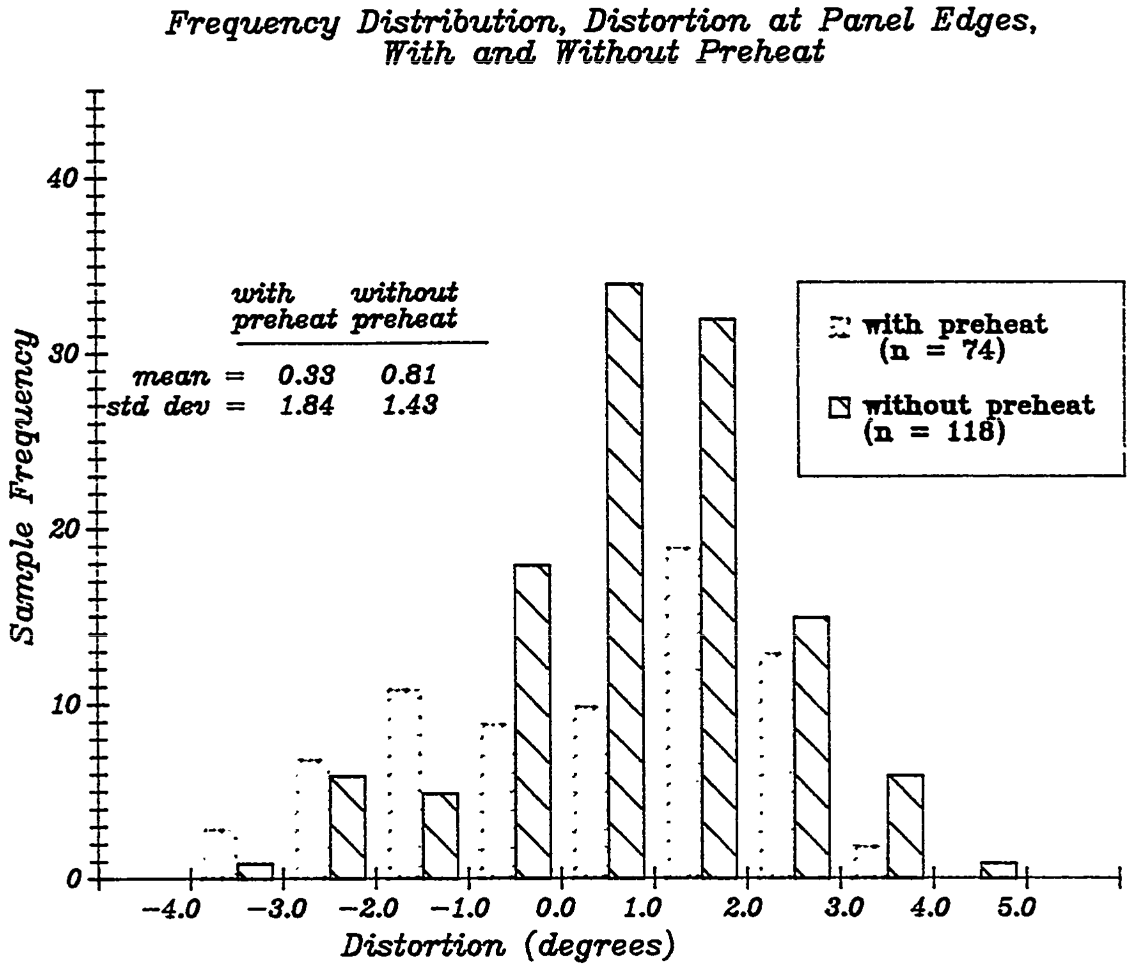


Figure 60. Frequency distribution of distortion measurements at edges for panels with and without preheat

Percent of sample measurements that exceed
(0 +/- n) degrees of distortion

panel interior			panel edges		
n	w/preheat	w/o preheat	n	w/preheat	w/o preheat
0.5	57 %	63 %	1.0	74 %	56 %
1.0	29 %	29 %	2.0	34 %	25 %
1.5	14 %	11 %	3.0	7 %	7 %
2.0	8 %	4 %	4.0	0 %	1 %
2.5	2 %	2 %	5.0	0 %	0 %
3.0	0 %	0 %			

As shown, the preheated panels provided comparable amounts of distortion to the nonpreheated panels. The percentage of sample locations that exceeded each of these various ranges of distortion are, if not identical, very close. Thus, it can be concluded that preheating did not reduce the distortion of the panel butt welds.

From the percentages listed above, it can be seen that greater distortion does occur at the edges than interior to the panel. For example, on the preheated panels, only 8 % of the total measurements interior to the panel exceeded +/- 2 degrees while 34 % exceeded this range at the panel edges. Undoubtably, this difference is the result of reduced restraint to distortion at the panel edges as comparsd to interior. Since this will always be the case at the butt edges, then it may be useful to increase restraint through use of a strongback transverse to the butt (underneath) at the edges. For the panels welded in this effort, the run-off tabs at the panel edges provided this added restraint to some degree, but were obviously too Small (approximately 6 inches wide and tacked on each side of the joint) to prevent the increased distortion at the edges. A 2-3 foot strongback, set tramsverse to the but and tacked every six inches should significantly reduce or possioly even sliminate this problem.

Further investigation must include preheating of the root pass. When using two torches adjacent to the butt, as in this effort, widening of the backing tape or manual taping of it to

the joint will not be successful. Some type of mechanical support will be required. Preheating may be better and more easily applied at the following stage in the panel construction process: fillet welding of panel longitudinal and framing. Since the welding of panel longitudinal and framing normally represent such a large proportion of the total ships welding (probably the greatest amount of welding at any single stage of construction), reduction of the weld distortion generated from this construction stage could significantly reduce overall distortion costs.

Further investigation should additionally include the use of higher preheat temperatures. Higher preheat temperatures will further reduce the cooling rate. However, care must be taken not to exceed maximum interpass temperatures that can be detrimental to the plate properties. In naval shipbuilding, this is a significant limitation in that an increasingly large amount of plating is of thinner high strength low alloy (HSLA) or high yield (HY-80/100) material. It is this thinner plating that distorts the greatest, often as "buckling distortion".

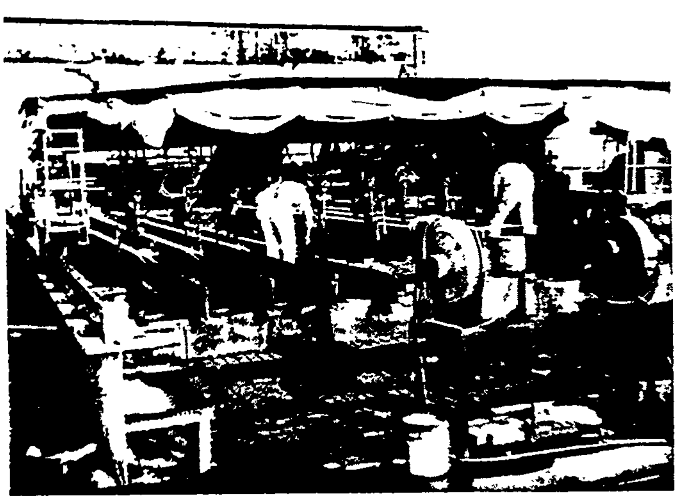
13.0 Water Coolant for Flange Stripping

In ship construction, it is common to manufacture tees by stripping the flanges from I-beams. When manufacturing a single tee at a time, this is usually accomplished with two torches running on a motor driven car and track. In manufacturing several tees at one time, this task may be accomplished with several torch heads attached to a motor-driven gantry that spans and traverses down the I-beams being cut. Figure 61 shows the gantry system at Ingalls Shipbuilding that will manufacture 10 tees at one time.

A common result of the flange stripping process is distortion in the tees produced. This distortion is caused by the hest of the cutting process which induces shrinkage in the web along the edge where the flanges were cut. The result is often a tee with a "bow" in both the plane of the flange and web as shown in Figure 52. In some cases there may also be a twist, or ratation of one end of the tee relative to the other.

Correction of this distortion is normally accomplished through line heating. Figure 63 shows line heating methods for removing distortion in the web and flange planes. As seen, this correction is accomplished through use of a "V-heat" pattern. in each case, heating is accomplished on the convex sids of the bow. In this manner, the convex side of the bow may be shrunk to the same length as the concave side thersby producing a straight tee in that plane.

If not corrected earlier, then the distortion in the tee must be removed in the fitting process. As shown in Figure 54. a strongback and wedge is normally used to force the tee to a straight condition for fitup. The result is increased fitup costs as well as added stresses to the structural assembl, that in turn. add to fitup and straigntening cost in future construction stages.



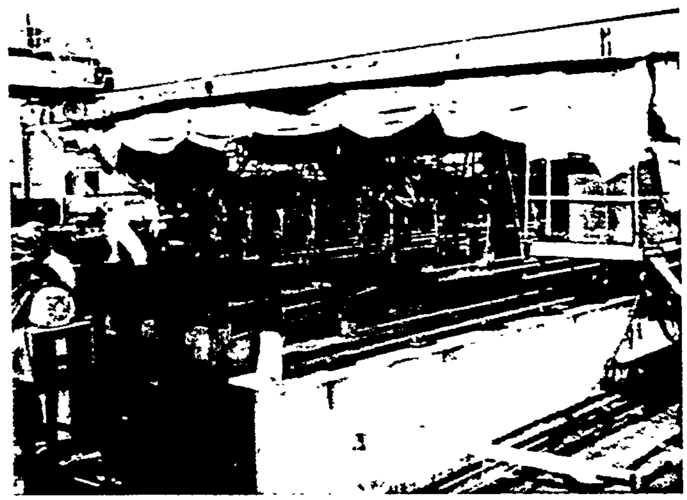
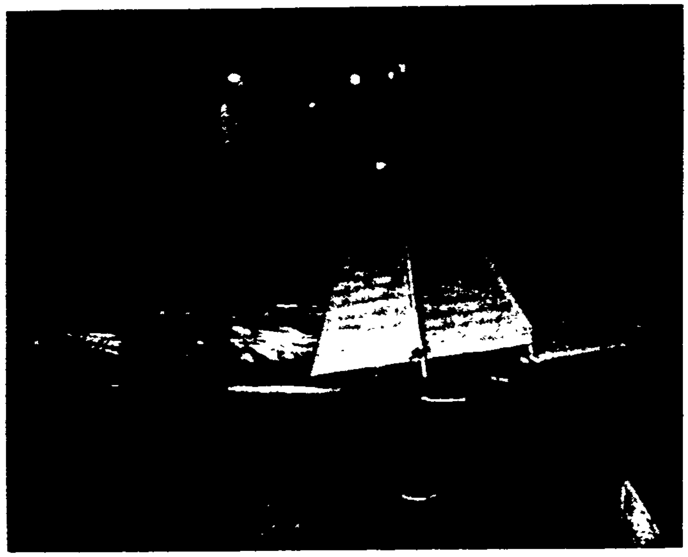
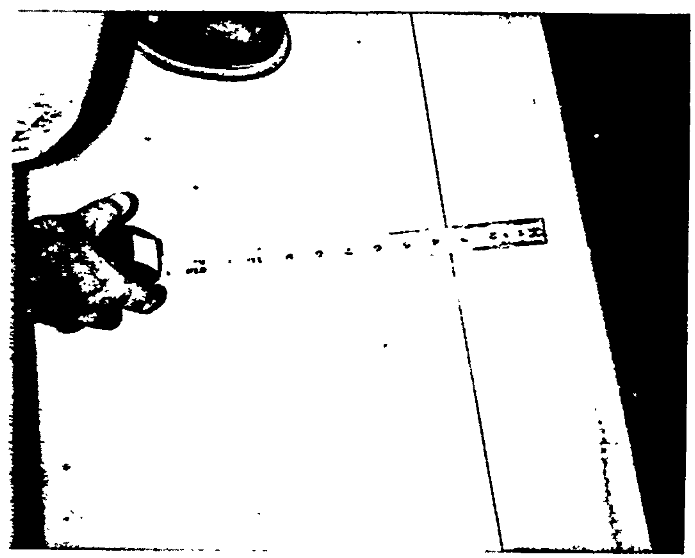


Figure 61. Flange stripping gantry system that can produce 10 tees at a time



40 ft tees in shop, prior to straightening

2-5/8 inch bow in one tee



3-1/2 inch bow in another

Figure 62. Distortion in tees from flange stripping process

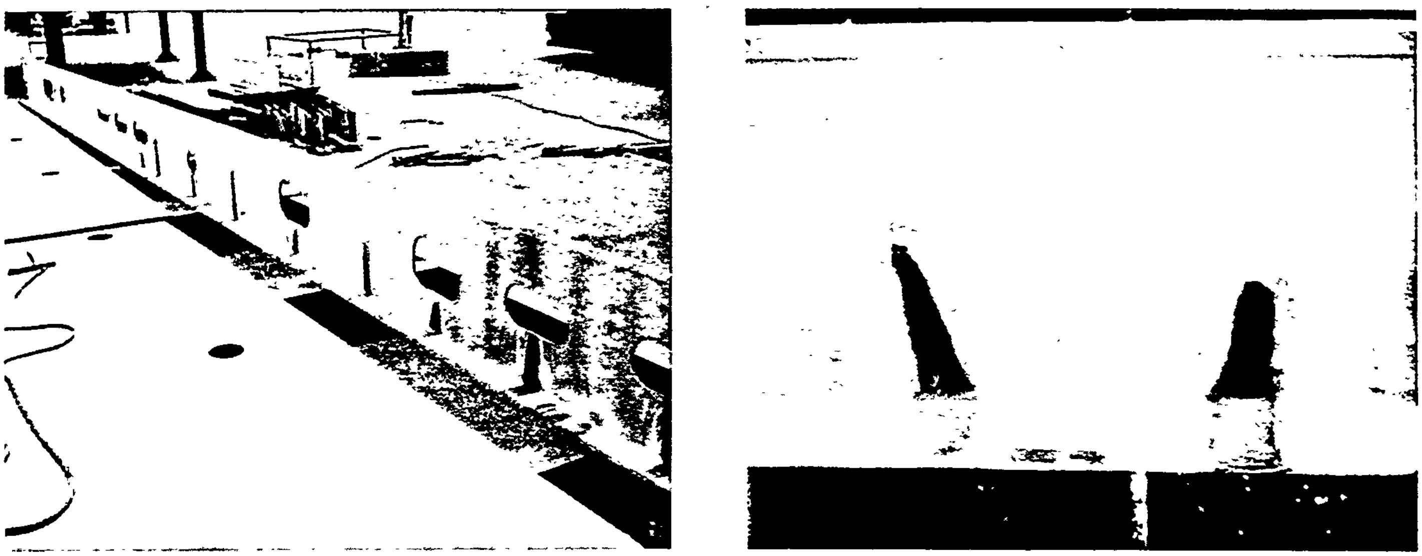


Figure 63. Vee heat patterns used to correct the distortion in tees produced from the flange stripping and hole cutting process

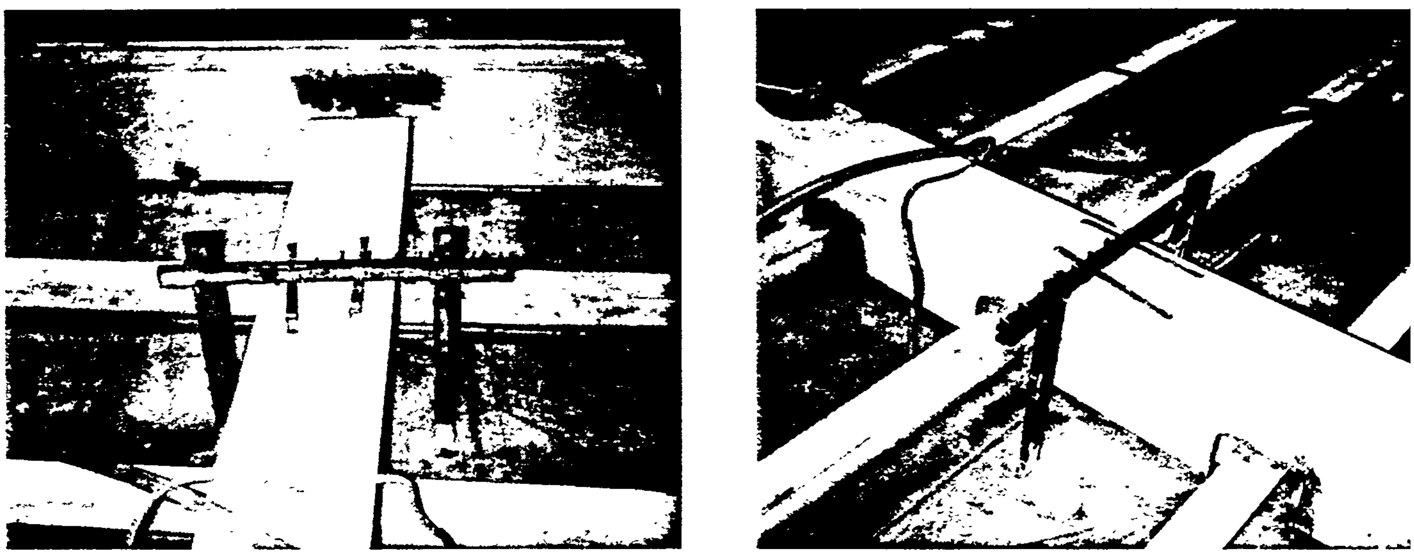


Figure 64. Fitting of a tee using a saddle and wedges

13.1 Test Method

Figure 65 shows the setup that is currently used on the gantry cutting system for steel tees at Ingalls Shipbuilding. In this effort, the extent of distortion reduction achieved through this application of water coolant was measured.

As shown in the figure, water is applied through a small tube that is attached to the torch carrriage. A small water stream is applied to the tee web at approximately 3 inches behind the torches. This stream is applied continuously throughout the length of the tee. The tee is held straight during the cutting effort by a clamping system, Shown in Figure 66, that holds each bottom flange rigid. In addition to maintaining the straightness of the tee for cutting purposes; the restraint of the clamping system assists in i-educing the tee distortion.

13.2 Distortion Measurements

The I-beams cut on the gantry machine normally include a large variety of sizes and weights. Lengths are normally 20', 30', 40' or 50'. From work in-process, a random sample of 120 I-beams that include 10 different beam sizes/weights in 20', 30' and 40' lengths were chosen and cut without water. A comparable sample of 101 I-beams of the same sizes, weights and lengths were randomly chosen and cut with a water coolant. Figure 67 shows the quantity in each sample by beam size, weight and length.

Distortion measurements were taken on the tees in both the plane of the web and flange, as shown in Figure 68. In each case, the tee was set on its flange and a wire was stretched along its length. A maximum distortion reading was found, measured using a dial caliper, and recorded. Tees were allowed to cool at least 1 hour prior to taking measurements.

A surprisingly large number of the tees, particularly those from the larger I-beam sizes, were found to be distorted with the flange concave, as shown in Figure 69. Specifically, 30 of 101 in the sample without water and 25 of 120 in the

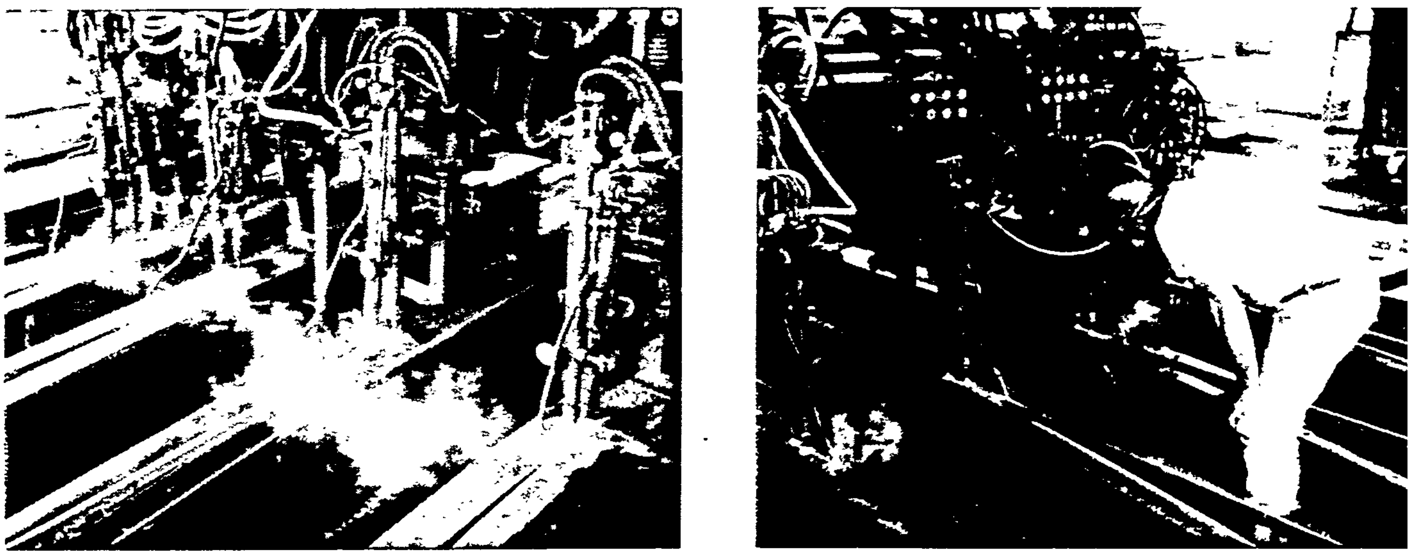


Figure 65. Application of water stream following flange cutting

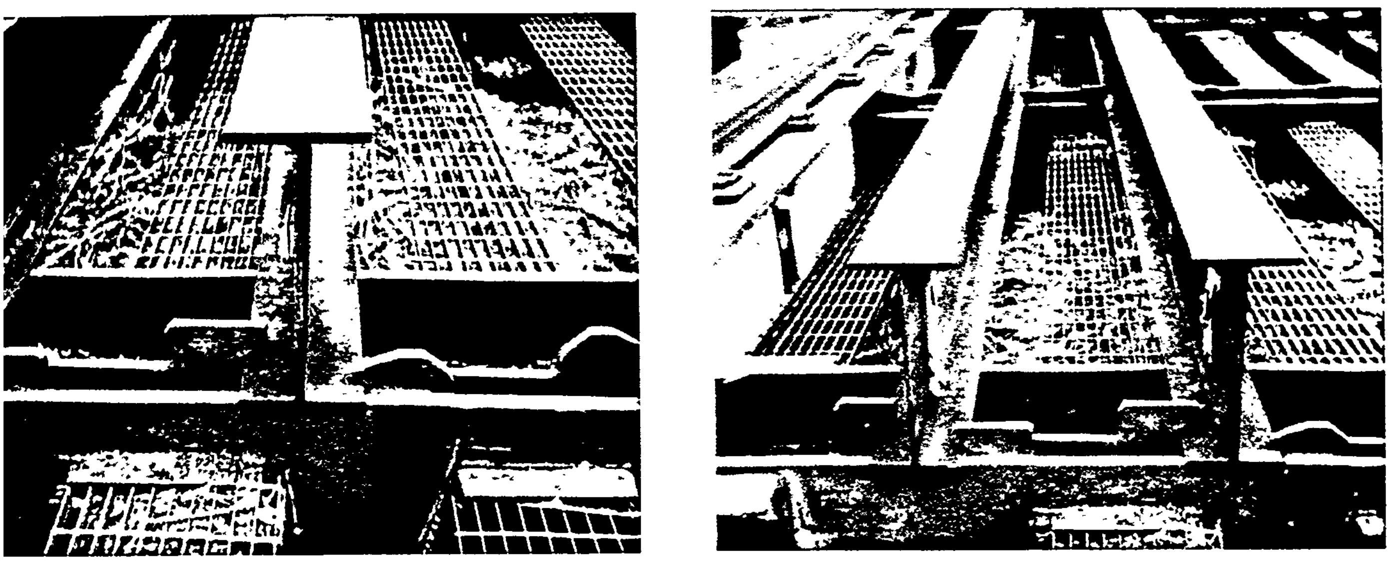


Figure 66. Clamping system in flange stripping process

Figure 67. Quantity of tees measured by size and length in the samples with and without water

Size of Tee	Without Water			With Water		
	Length			Length		
	20 ft	30 ft	40 ft	20 ft	30 ft	40 ft
10 x 12	7	19	8	6	4	10
10 x 26	1			2		
12 x 14	8	11	3	5	6	3
12 x 16	6	1		6	4	
12 x 22		1			3	
12 x 26	1			8		
12 x 30		11			7	13
14 x 22	5		20	10		11
14 x 26			1			2
16 x 40		7	10		7	13
	Total sample = 120 tees			Total sample = 101 tees		

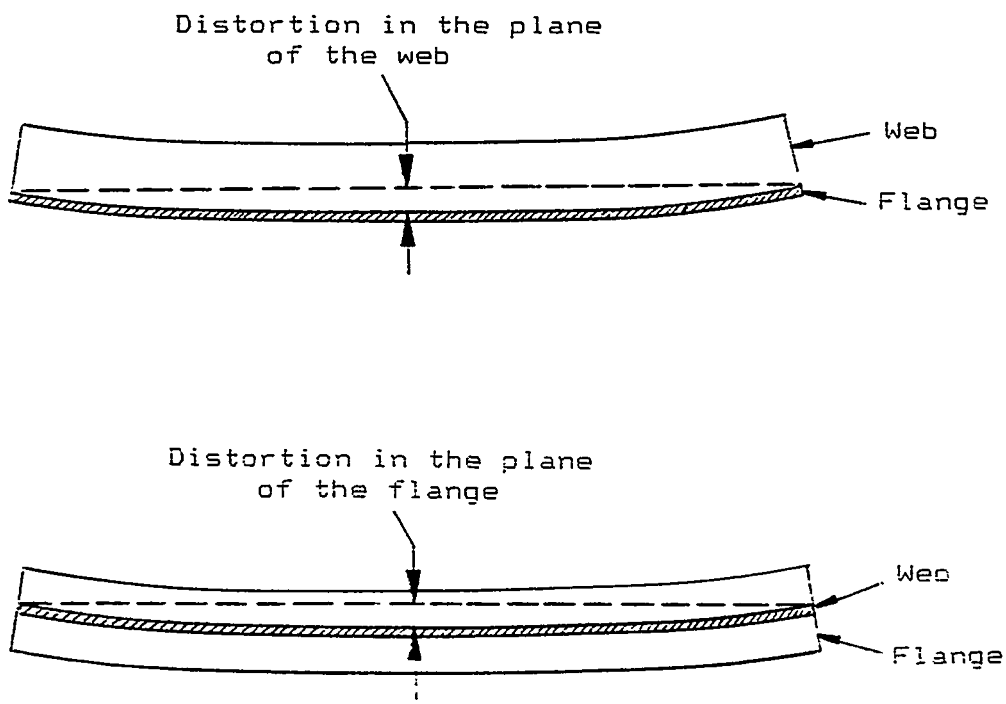
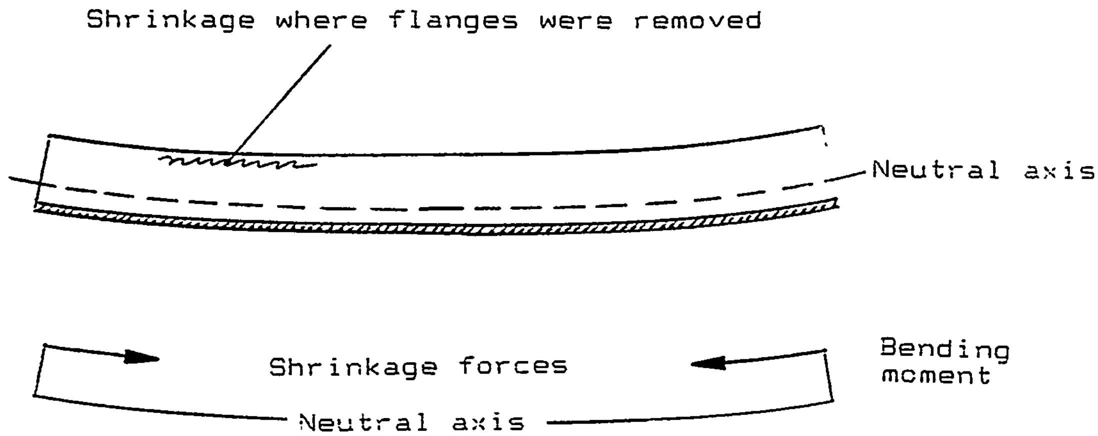
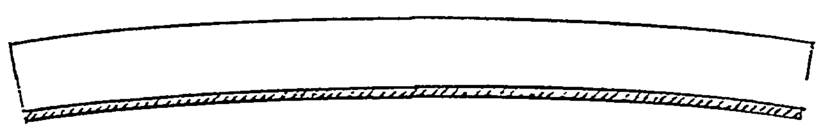


Figure 68. Tee distortion measurements in the plane of the web and flange



Expected direction of distortion in the plane of the web



Distortion observed in some tees opposite to the expected direction

Figure 69. Distortion in the plane of the web, observed in some tees opposite to the expected direction

sample with water were of this configuration. Since shrinkage is induced on the side of the web where the flanges are removed, then the location of this shrinkage relative to the neutral axis of the tee should cause a bow in the opposite direction. Sample measurements in the plane of the web which were distorted as in Figure 69 were assigned a negative value, denoting this condition.

13.3 Analysis of Measurements

Sample measurements for distortion in the web and flange planes are shown in Table 7. A frequency distribution of these measurements is provided in Fiqurs 70. As seen in this chart and the table of minimium and maximum measurements below, a reduction in the range of distortion was observed for the tees using a water coolant:

	Plane of Flange		Plane of Web	
	without water	with water	without water	with water
minimum value =	0.057"	0.068"	-1.991"	-1.215"
maximum value =	2.065"	1.421"	2.442"	1.992"
range =	2.008"	1.353"	4.433"	3.207"

In calculating the sample mean and standard deviation valuess a similar reduction in distortion is seen in the tess cut with water coolant:

	Plane of Flange			Plane of Web		
	without water	with water	(delta)	without water	with water	(delta)
sample mean =	0.544"	0.496"	0.048"	0.459"	0.218"	0.241"
sample std dev =	0.452"	0.339"	0.113"	0.823"	0.626"	0.197"

Table 7. Distortion measurements in the plane of the flange and web for tees produced with and without water

Sample 1: Without Water

Meas #	I-beam Size	Lgth (ft)	Plane of Flg (in)	Plane of Web (in)	Meas #	I-beam Size	Lgth (ft)	Plane of Flg (in)	Plane of Web (in)	Meas #	I-beam Size	Lgth (ft)	Plane of Flg (in)	Plane of Web (in)
1	10x12	20	0.120	0.824	41	10x12	30	0.791	1.336	81	10x12	40	0.665	2.284
2	10x12	20	0.359	0.709	42	10x12	30	0.933	1.320	82	10x12	40	0.520	1.181
3	10x12	20	0.172	0.490	43	10x12	30	0.725	1.431	83	10x12	40	0.684	2.094
4	10x12	20	0.244	0.811	44	10x12	30	0.411	1.279	84	10x12	40	1.036	2.313
5	10x12	20	0.479	0.632	45	10x12	30	0.898	1.432	85	10x12	40	0.277	2.342
6	10x12	20	0.082	0.766	46	10x12	30	0.470	1.715	86	10x12	40	0.46	1.214
7	10x12	20	0.483	0.648	47	10x12	30	0.188	1.317	87	12x14	40	1.752	1.152
8	10x26	20	0.246	0.473	48	12x14	30	0.314	0.524	88	12x14	40	1.543	0.985
9	12x14	20	0.234	0.280	49	12x14	30	0.450	0.692	89	12x14	40	1.339	1.146
10	12x14	20	0.312	0.423	50	12x14	30	1.504	0.756	90	14x22	40	1.101	0.600
11	12x14	20	0.321	0.310	51	12x14	30	0.412	0.826	91	14x22	40	0.454	0.121
12	12x14	20	0.072	0.173	52	12x14	30	0.569	0.755	92	14x22	40	1.065	0.366
13	12x14	20	0.303	0.270	53	12x14	30	0.430	0.625	93	14x22	40	1.555	0.614
14	12x14	20	0.248	0.319	54	12x14	30	0.240	0.772	94	14x22	40	0.605	0.177
15	12x14	20	0.250	0.297	55	12x14	30	0.560	0.643	95	14x22	40	0.562	-0.028
16	12x14	20	0.222	0.272	56	12x14	30	0.390	1.042	96	14x22	40	0.488	0.100
17	12x16	20	0.145	0.260	57	12x14	30	0.406	0.750	97	14x22	40	1.539	0.239
18	12x16	20	0.372	0.447	58	12x14	30	0.250	1.163	98	14x22	40	0.888	[illegible]
19	12x16	20	0.371	0.444	59	12x16	30	0.375	0.294	99	14x22	40	2.055	-0.455
20	12x16	20	0.524	0.280	60	12x22	30	0.222	0.522	100	14x22	40	0.257	0.475
21	12x16	20	0.480	0.384	61	12x30	30	0.107	0.132	101	14x22	40	1.303	0.345
22	12x16	20	0.350	0.390	62	12x30	30	0.132	0.170	102	14x22	40	0.684	0.375
23	12x26	20	0.089	0.221	63	12x30	30	0.193	-0.400	103	14x22	40	1.245	-0.749
24	14x22	20	0.100	-0.119	64	12x30	30	0.070	-0.385	104	14x22	40	0.332	0.429
25	14x22	20	0.265	0.094	65	12x30	30	0.155	0.253	105	14x22	40	0.702	0.336
26	14x22	30	0.328	0.158	66	12x30	30	0.071	-0.430	106	14x22	40	1.436	0.475
27	14x22	20	0.295	0.243	67	12x30	30	0.057	0.313	107	14x22	40	0.445	0.275
28	14x22	30	0.148	0.164	68	12x30	30	0.145	0.127	108	14x22	40	0.420	0.259
29	10x12	30	0.226	1.495	69	12x30	30	0.249	0.105	109	14x22	40	[illegible]	0.222
30	10x12	30	0.118	1.103	70	12x30	30	0.240	-0.175	110	14x22	40	0.612	-0.333
31	10x12	30	0.156	1.431	71	12x30	30	0.302	[illegible]	111	16x40	40	0.355	-0.227
32	10x12	30	0.153	1.207	72	16x40	30	0.155	-0.125	112	16x40	40	0.244	-0.337
33	10x12	30	0.260	1.430	73	16x40	30	0.309	-1.654	113	16x40	40	1.217	[illegible]
34	10x12	30	0.723	1.255	74	16x40	30	0.304	-0.295	114	16x40	40	1.712	-0.534
35	10x12	30	0.313	1.217	75	16x40	30	0.557	-1.315	115	16x40	40	1.522	-1.237
36	10x12	30	0.720	1.253	76	16x40	30	0.560	-0.590	116	16x40	40	1.351	-1.771
37	10x12	30	0.300	1.314	77	16x40	30	0.253	-0.750	117	16x40	40	1.732	-1.667
38	10x12	30	0.756	1.232	78	16x40	30	0.602	-0.696	118	16x40	40	1.154	-0.344
39	10x12	30	0.532	1.424	79	10x12	40	0.779	2.055	119	16x40	40	0.091	-1.677
40	10x12	30	1.148	1.522	80	10x12	40	0.429	0.942	120	16x40	40	0.365	-0.237

Table 7. (continued)

Sample 2: With Water

Meas #	I-beam Size	Lgth (ft)	Plane of Flg (in)	Plane of Web (in)	Meas #	I-beam Size	Lgth (ft)	Plane of Flg (in)	Plane of Web (in)	Meas #	I-beam Size	Lgth (ft)	Plane of Flg (in)	Plane of Web (in)
1	10x12	20	0.196	0.494	34	14x22	20	0.265	-0.125	68	10x12	40	0.521	1.351
2	10x12	20	0.243	0.318	35	14x22	20	0.292	-0.450	69	10x12	40	0.770	0.700
3	10x12	20	0.285	0.357	36	14x22	20	0.640	0.221	70	10x12	40	0.185	1.243
4	10x12	20	0.375	-0.120	37	14x22	20	0.317	0.229	71	10x12	40	1.215	1.500
5	10x12	20	0.150	0.386	38	10x12	30	1.062	0.992	72	10x12	40	1.320	1.479
6	10x12	20	0.289	0.314	39	10x12	30	1.151	1.031	73	10x12	40	1.251	1.019
7	10x26	20	0.292	0.734	40	10x12	30	0.462	1.010	74	12x14	40	0.714	1.025
8	10x26	20	0.199	0.164	41	10x12	30	0.192	1.200	75	12x14	40	0.101	0.327
9	12x14	20	0.255	0.060	42	12x14	30	0.858	0.561	76	12x14	40	0.751	1.112
10	12x14	20	0.145	-0.040	43	12x14	30	0.222	0.661	77	14x22	40	0.462	0.319
11	12x14	20	0.380	0.355	44	12x14	30	0.252	0.601	78	14x22	40	0.630	0.315
12	12x14	20	0.255	0.041	45	12x14	30	0.728	0.518	79	14x22	40	0.170	0.113
13	12x14	20	0.579	0.195	46	12x14	30	0.800	0.540	80	14x22	40	0.355	0.265
14	12x16	20	0.102	0.190	47	12x14	30	0.917	-0.340	81	14x22	40	0.205	0.524
15	12x16	20	0.129	0.059	48	12x16	30	0.697	0.125	82	14x22	40	0.796	0.116
16	12x16	20	0.683	0.130	49	12x16	30	0.340	0.232	83	14x22	40	0.155	0.237
17	12x16	20	0.239	0.150	50	12x16	30	0.182	0.175	84	14x22	40	0.262	0.230
18	12x16	20	0.267	0.037	51	12x16	30	1.214	0.392	85	14x22	40	0.320	0.337
19	12x16	20	0.619	0.201	52	12x22	30	0.649	-0.621	86	14x22	40	0.955	0.135
20	12x26	20	0.301	-0.070	53	12x22	30	0.715	-0.695	87	14x26	40	0.440	-0.350
21	12x26	20	0.396	-0.210	54	12x22	30	0.528	-0.675	88	14x26	40	1.255	-0.625
22	12x26	20	0.090	-0.061	55	12x30	30	0.100	0.359	89	16x40	40	0.347	0.625
23	12x26	20	0.365	-0.200	56	12x20	30	0.068	0.236	90	16x40	40	0.518	-0.341
24	12x26	20	0.232	-0.224	57	16x40	30	0.251	-0.722	91	16x40	40	0.276	-1.010
25	12x26	20	0.199	0.194	58	16x40	30	0.115	0.617	92	16x40	40	0.531	-0.205
26	12x26	20	0.211	-0.057	59	16x40	30	0.317	0.498	93	16x40	40	1.421	0.157
27	12x26	20	0.232	0.115	60	16x40	30	0.387	-0.882	94	16x40	40	0.578	-0.895
28	14x22	20	0.310	-0.140	61	16x40	30	0.212	-0.532	95	16x40	40	0.232	0.270
29	14x22	20	0.255	-0.085	62	16x40	30	0.109	0.529	96	16x40	40	0.515	0.124
30	14x22	20	0.548	0.296	63	16x40	30	0.393	0.741	97	16x40	40	0.771	0.225
31	14x22	20	0.280	0.122	64	10x12	40	0.748	1.011	98	16x40	40	0.648	-1.015
32	14x22	20	0.603	0.209	65	10x12	40	1.301	1.611	99	16x40	40	0.756	-0.385
33	14x22	20	0.261	-0.139	66	10x12	40	0.877	1.722	100	16x40	40	0.779	-1.215
					67	10x12	40	1.130	1.131	101	16x40	40	0.915	-1.065

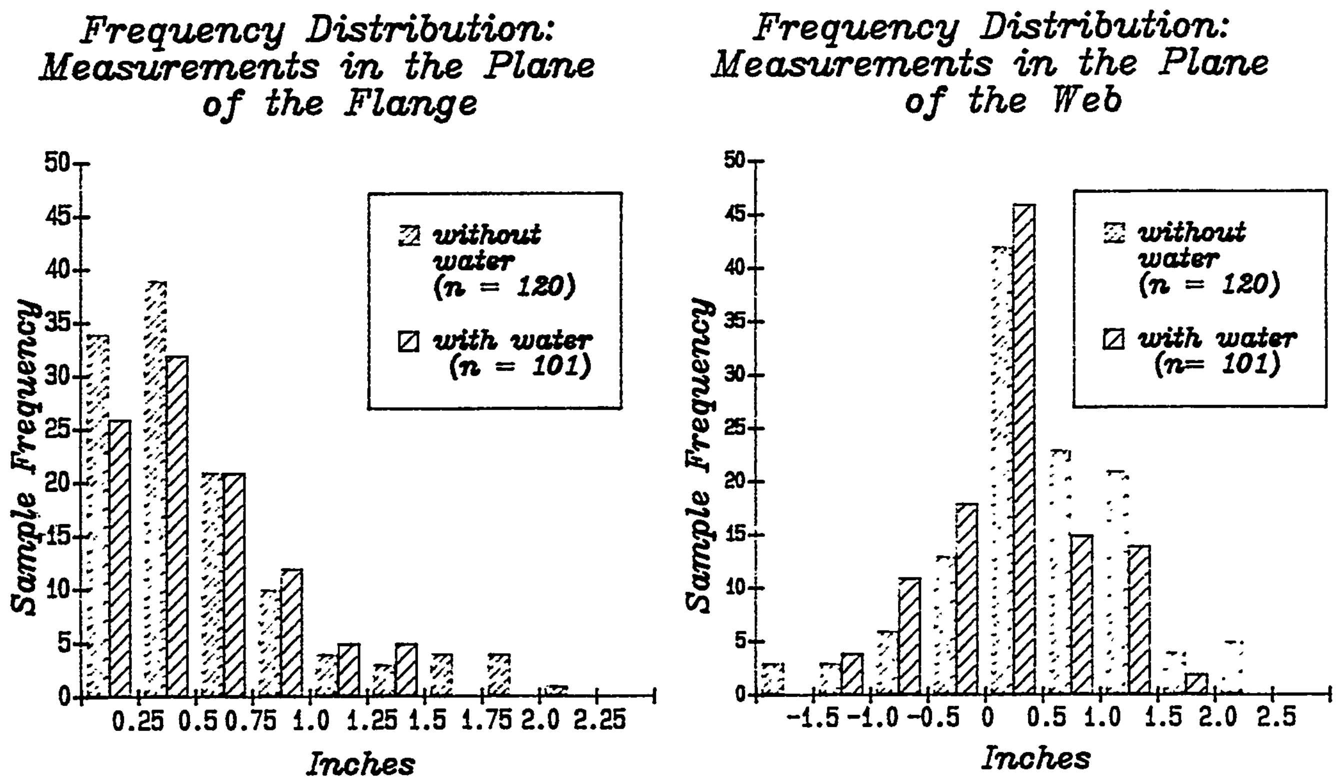


Figure 70. Frequency distribution of measurements in the plane of the flange and web for tees produced with and without water

In the plane of the flange, a mean reduction in distortion = 0.048" was measured. As a percentage change, this may be calculated as:

$$(0.544 - 0.496)/0.544 = 8.8\ \%\ \text{reduction.}$$

In the plane of the web, a mean reduction in distortion = 0.241" was measured. As a percentage change, this may be calculated as:

$$(0.459 - 0.218)/0.459 = 52.5\ \%\ \text{reduction.}$$

Statistical testing of these claims for reduction in tee distortion emphasized the results above. For the samples measured in the plane of the web, a test statistic value of $z = 2.47$ established that a mean reduction in distortion exists at a 95 % level of confidence (see Appendix for explanation of statistical methods).

For the samples measured in the plane of the flange, however, statistical testing produced a test statistic value of $z = 0.90$ which causes a rejection at a 95 % canfidence level (z must be greater than 1.645). Thus, based on the variability seen in the sample measurements, there is a greater than 5 % chance that the difference in mean distortion between the flanges cut with and without water is simply a result of randomness in the sampling effort. The question, however, is how much greater a chance? From the calculated test statistic, it can be shown that a reduction in mean distortion could be established at an 61.6 % level of confidence. Given this relatively high confidence level and the distortion reduction already established in the plane of the web, it can be safely concluded that distorting was reduced in the plane of flange through use of a water coolant.

In summary, it is seen that the application of a water stream directly behind the torches will signifiantly reduce the the distortion of the tee beam produced. In this effort, mean distortion was reduced 52.5 % in the plane of the web and 8.8 % in the plane of the flange.

14.0 Induction Straightening

In the fabrication of ships structure, local heating at welded joints causes plating distortion. On decks, bulkheads, and shell plating, this distortion often produces the "hungry horse" look familiar to all fabricators. When exceeding close specification tolerances for distortion, costly straightening efforts are required. The most common method for accomplishing this straightening is through the use of flame heating. Heat is applied using an oxy-acetylene torch and then quickly cooled through a combination spray of air and water. An initial pass is made on the smooth side of the plating directly above the stiffener locations, as shown in Figure 71. Shrinkage is induced that forces the plating to a flatter plane between stiffeners.

Induction straightening relies upon this same shrinkage effect to correct distortion in steel plating. In this case, however, heat is generated by induction. Alternating current within the induction unit produces a rapidly expanding and collapsing electromagnetic field. when this field is imposed through the steel plating, eddy currents are generated within the plating material. Resistance of the material to these currents generates heat. Control over the magnetic field strength and/or time of application provides control over the amount of heat produced.

In this study, the effectiveness of induction straightening on the thinner plating increasingly associated with U.S. naval construction was investigated. The induction system used in this effort was the Terac-16 system prnduced bY Elva Induksjon a.s., Norway.

14.1 Equipment Description and Operation

The system consists of two basic components: (1) a three phase high frequency converter that is connected by a flexible power cable to (2) a manually positioned induction heating unit, as shown in Figure 72.

Converter unit dimensions are approximately 60" long, 21.5" wide, 32.5" high with a weight of 440 pounds. The

Figure 71. Flame straightening pass directly above deck longitudinals to correct distortion in deck plating

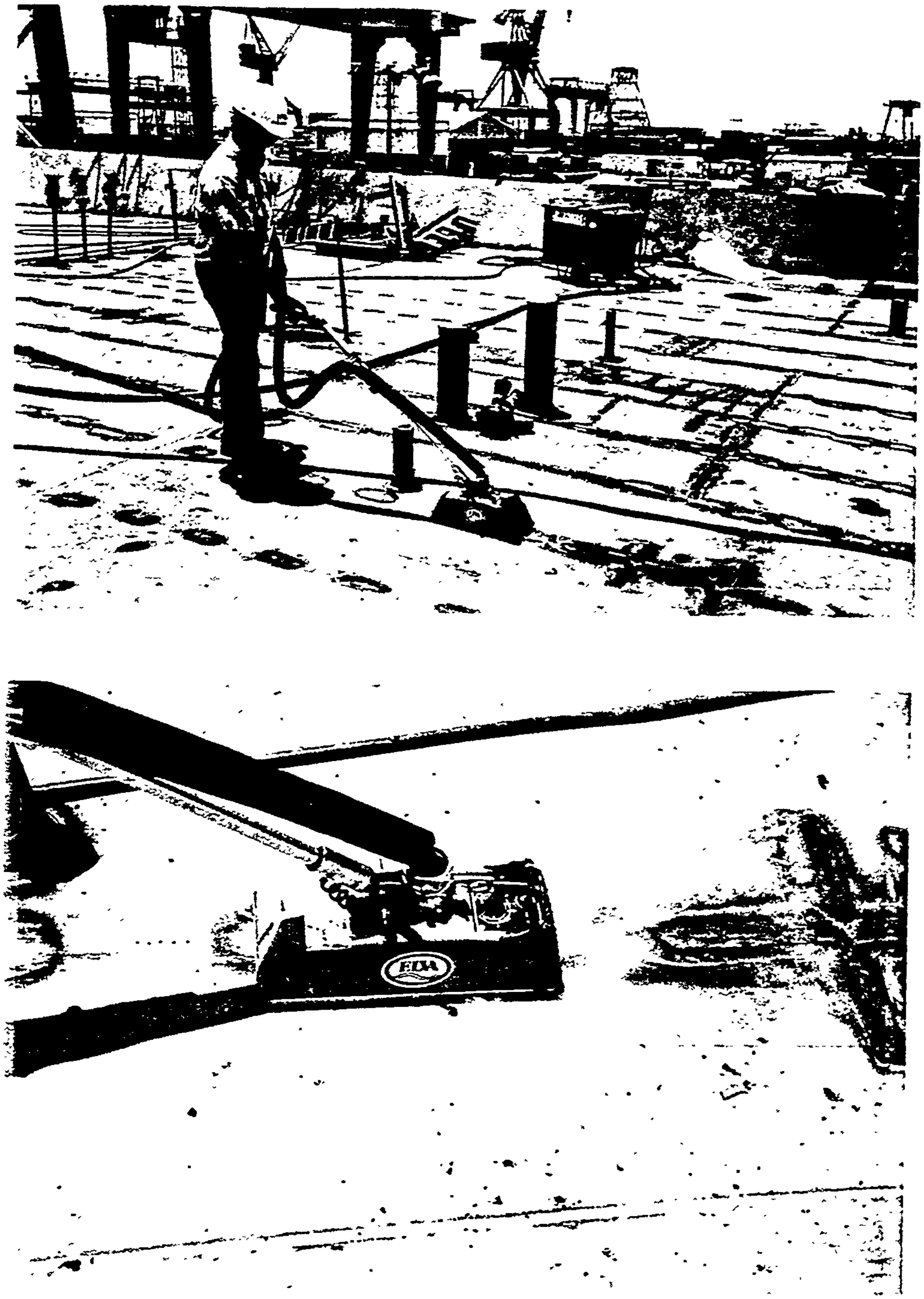


Figure 72. Induction straightening system including a high frequency converter (background, top photo) and induction heating unit (bottom photo)

converter unit is mounted on wheels for movement across a flat deck. The inductor unit is approximately 15" long, 6" wide, 8" high with a weight of 20 pounds without the handle.

Operation of the induction system is simple. The frequency converter provides a controlled output power (16 kw) to the induction unit. The induction unit produces the magnetic field which generates heat in the form of a concentrated stripe approximately 6.5" x 0.375". A dial control on the inductor head is used to preset the heating time for the particular plate thickness being straightened, and whether surface or through heating is required. The power is manually switched on by a button on the inductor unit handle and is automatically switched off after the preset heating time. During operation, electromagnets within the inductor head provide clamping to the plating surface.

Start-up preparation simply requires making two connections: a compressed air supply to the inductor head for cooling, and a fixed power cable from the frequency converter to a three phase supply.

14.2 Test Method

The effectiveness of the induction unit in straightening thinner plating was investigated through use on two hull blocks, #305 2nd and 1st platforms on CG-65. The dimensions of each platform were approximately 36 by 52 feet. Plating was 0.25" and 0.213" Mil-S-226988B ABS grade DH-36, Class U high strength steel on the 2nd platform, and 0.l68" Mil-S-2465(SH) type 1, class 1 high strength low alloy (HSLA-8O) Steel on the 1st platform. Longitudinal spacing ranged from 24" to 27". Spacing between frame members was 8'.

Straightening of each platform was accomolished prior to stacking of the deck level above. Both units were shipshape during straightening.

In the same manner as flame straigtening, induction straightening is most effectively accomplished through the use of various patterns. With vendor assistance, patterns as

provided in Figures 73 and 74 were employed. Because of the relatively large distortion in the thinner decks chosen, a three pass pattern was required, with a forth pass used only where necessary:

1st pass -- directly over the longitudinal, spaced approximately 4-6".
2nd pass -- between the 1st pass heating zones and approximately 0.75" away from the stiffener center toward the side with the most distortion.
3rd pass -- to the side with the greatest remaining distortion, either between the 2nd pass heating zones or on the opposite side of the longitudinal as a mirror image of the 2nd pass.
4th pass -- cross pattern interior to the longitudinals, only in locations still out-of-tolerance.

Timing of the induction unit was set to provide "through" heating Which could be visually seen on the underside of the plating as a dark red color for a period of 2-3 seconds. Through heating accomplishes straightening by shrinking the plating uniformly through its thickness.

Prior to straightening efforts, measurements were taken to locate areas out of tolerance. Although Mil-Std-l689(SH) requirements allow up to 0.625" unfairness for the tested plating thicknesses and stiffener spacings, this tolerance was known to be excessive to support fitting of squipment foundations for berthing component bases in those areas. Consequently. a "working" tolerance of 0.375" was invoked to meet the fitting requirements. Deck areas Outside this~ working tolerance were identified.

Distortion measurements were taken at the midpoint between longitudinals at each frame location. At each location measurements were taken using an inside dial caliper to a machined straight edge set across the longitudinals as shown in Figure 75. Prior to taking measurements after each pass, cooling of the deck to ambient was allowed.

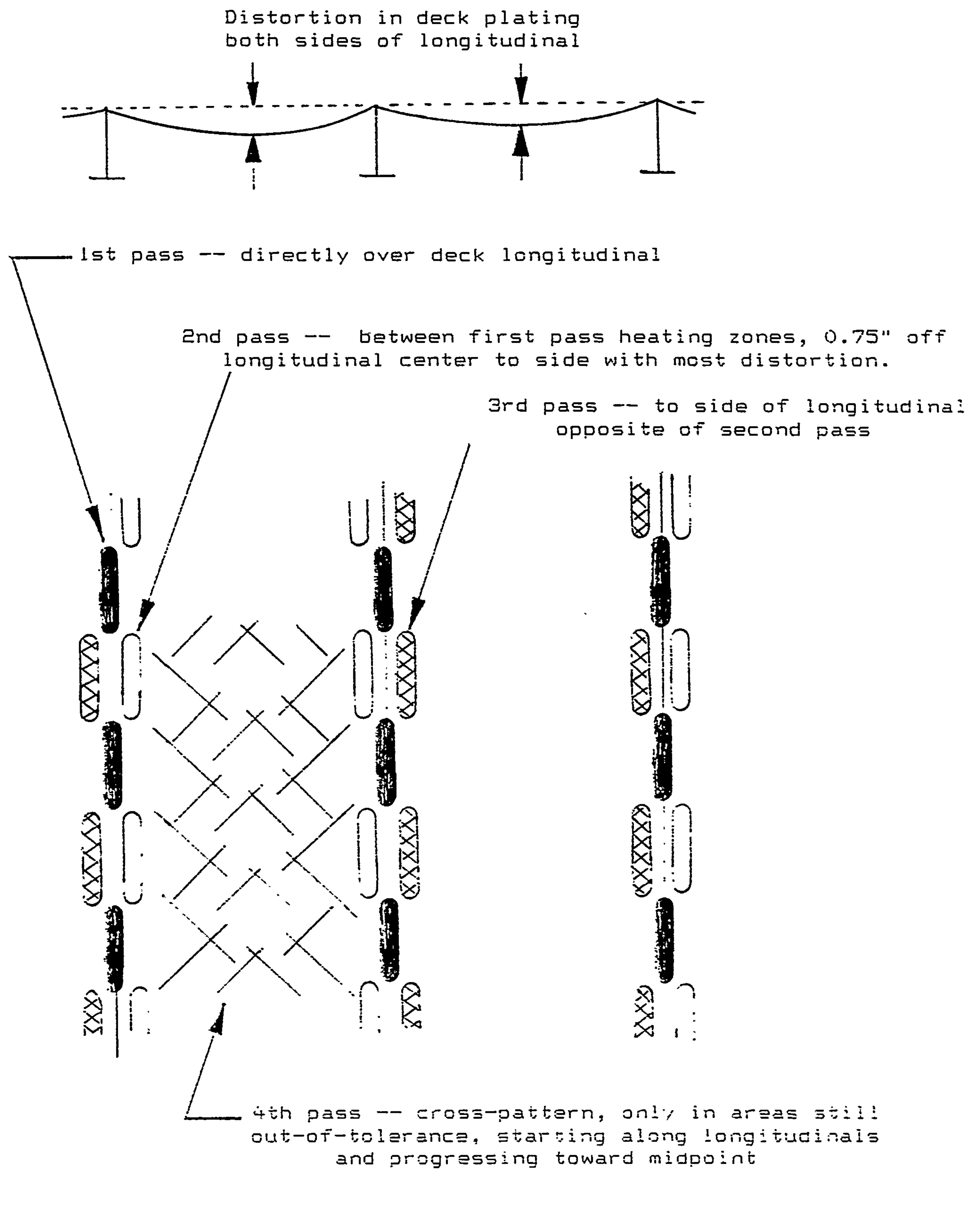


Figure 73. Induction straightening pattern of application, out-of-tolerance distortion on both sides of deck longitudinal

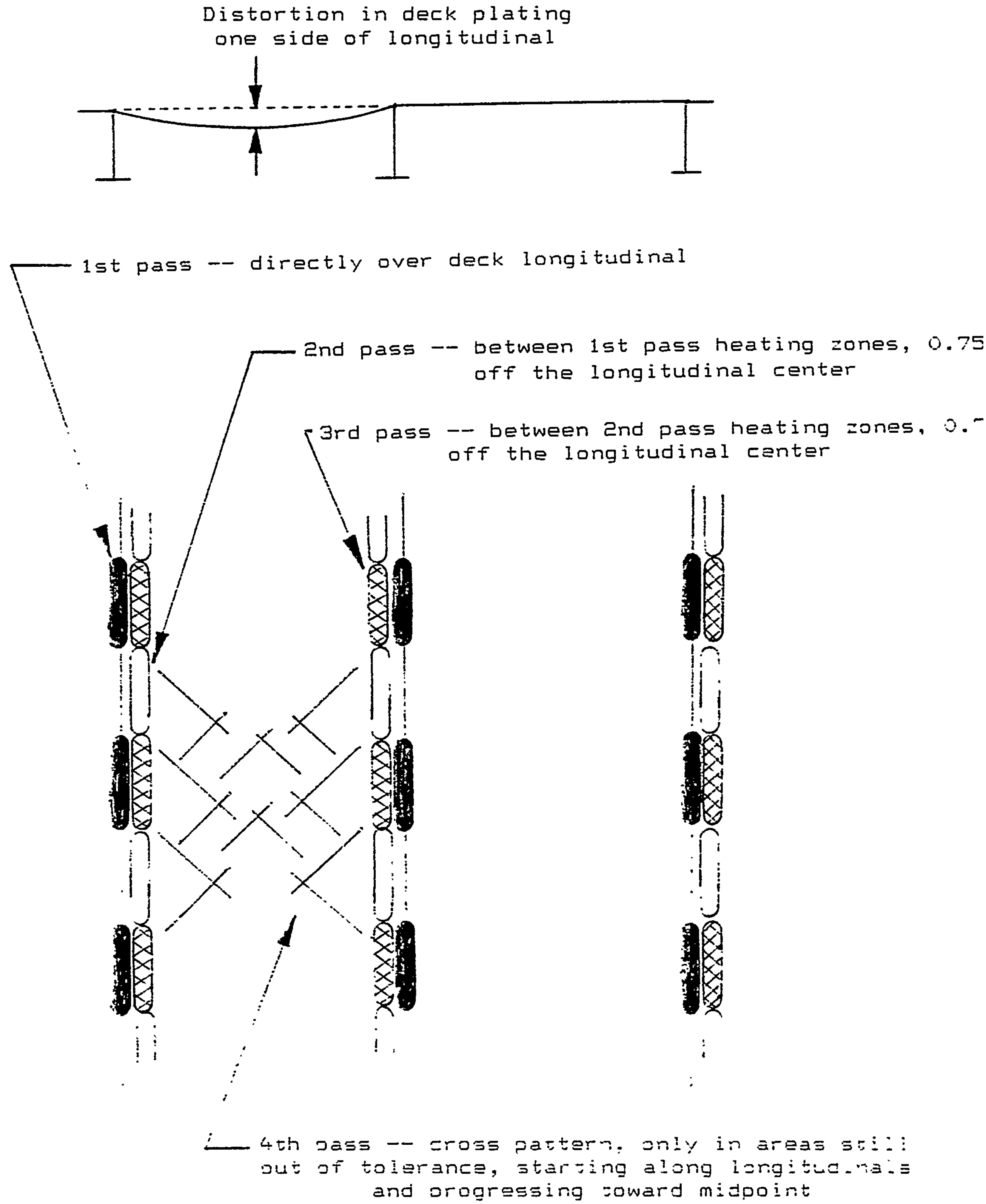


Figure 74. Induction straightening pattern of application, out-of-tolerance distortion on one side of longitudinal

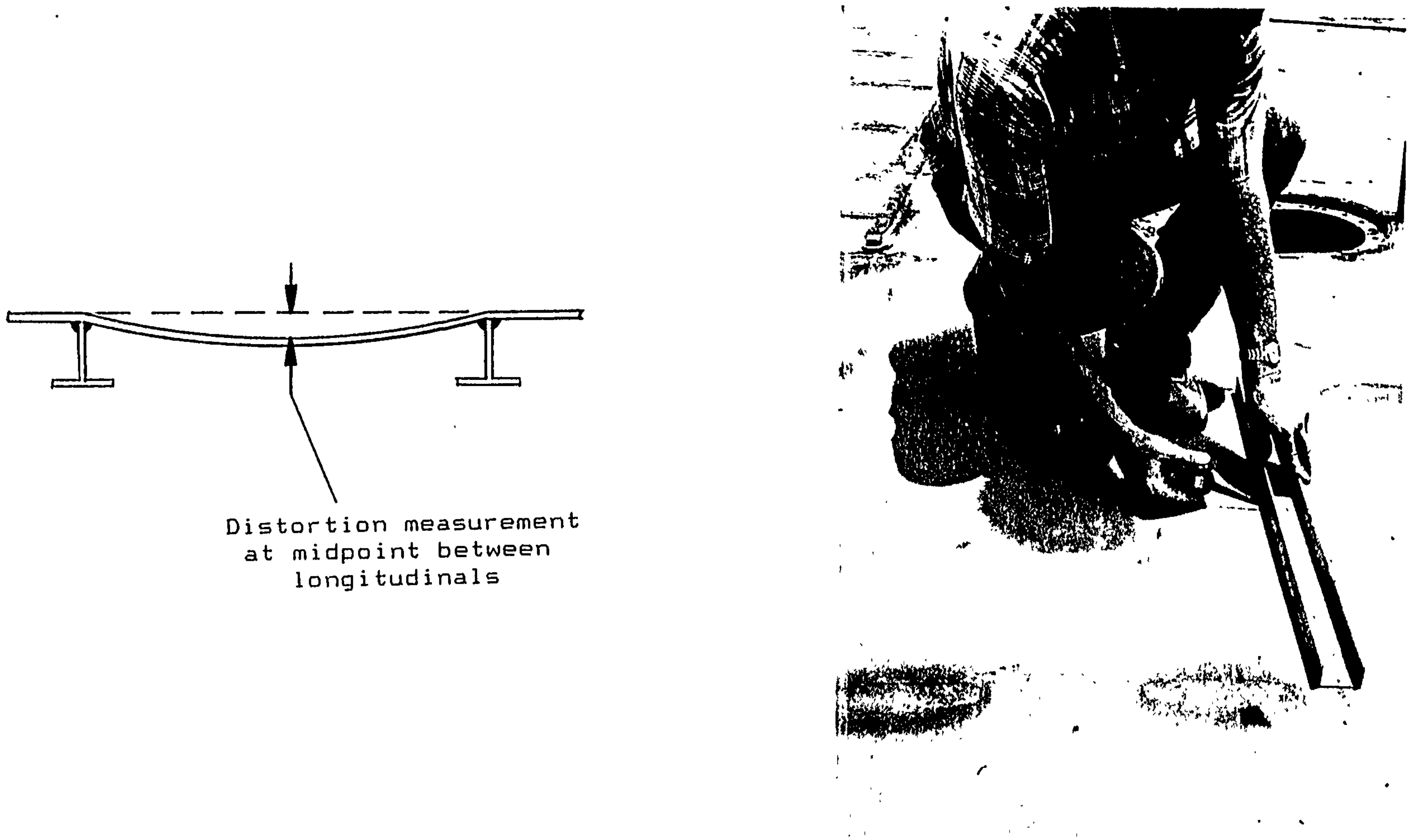


Figure 75. Distortion measurement at midpoint between longitudinals

Straightening was accomplished in the out of tolerance areas using the three pass pattern described previously. After each pass, distortion measurements were taken again to determine those areas still out of tolerance and the effects of each completed pass.

14.4 Analysis of Measurements

The distortion measurements taken prior to straightening and then after each pass are provided in Tables 8 and 9. For those taken prior to straightening, 82 and 174 locations were identified out-of-tolerance on the "2nd and Ist platforms, respectively. The disparity in distortion in the two platforms can be attributed to the large amount of 0.188" plating in in the 1st platform.

Breakdown of these out-of-tolerance locations by plate thickness showed:

2nd platform -- 52 locations on (2.250" plate
-- 30 locations on 0.313" plate

1st platform -- all 174 locations on 0.188" plate

Average unfairness of the out-of-tolerance locations on the 2nd platform was 0.596" with a maximum unfairness equal to 0.863". For the 1st platform, the average of the out-of-tolerance locations was 0.585" with a maximum unfairness equal to 0.996".

The performance of each induction straightening pass in terms of improvement to tolerance showed a distinct difference between the two platforms. These differences are shown in the table below and are illustrated in a frequency distribution of the measurements in Figure 76.

Table 8. 303 unit, 1st platform, distortion measurements between deck longitudinals after each induction pass

Measured between Longl's	@ Frame	Plate Size	Distortion Measurements (inches) Initial	1st Pass	2nd Pass	3rd Pass	Final
L2/L3-P	351	3/16	0.387	0.395	0.338	0.33	
L4/L5-S	351	3/16	0.377	0.512	0.615	0.527	0.635
L8/L9-S	352	3/16	0.569	0.427	0.278	0.196	
CL/L1-P	353	3/16	0.522	0.436	0.407	0.369	
L1/L2-S	353	3/16	0.441	0.233	0.014	-0.088	
L3/L4-S	353	3/16	0.642	0.671	0.62	0.578	0.51
L5/L6-S	353	3/16	0.604	0.607	0.535	0.505	0.464
L8/L9-S	353	3/16	0.751	0.602	0.548	0.527	0.536
CL/L1-P	354	3/16	0.426	0.123	-0.066	-0.069	
L1/L2-S	354	3/16	0.439	0.458	0.46	0.395	0.412
L2/L3-P	354	3/16	0.843	0.845	0.776	0.647	0.573
L3/L4-S	354	3/16	0.514	0.482	0.461	0.411	
L5/L6-P	354	3/16	0.592	0.628	0.567	0.535	0.547
L5/L6-S	354	3/16	0.59	0.617	0.548	0.53	0.487
L8/L9-S	354	3/16	0.65	0.535	0.435	0.394	0.398
CL/L1-P	355	3/16	0.425	0.256	0.263	0.238	
L2/L3-P	355	3/16	0.856	0.919	0.934	0.795	0.769
L3/L4-P	355	3/16	0.521	0.491	0.49	0.111	
L5/L6-P	355	3/16	0.577	0.553	0.444	0.415	0.338
L8/L9-S	355	3/16	0.644	0.57	0.439	0.379	0.338
L2/L3-P	356	3/16	0.738	0.842	0.75	0.76	0.749
L3/L4-P	356	3/16	0.525	0.505	0.541	0.227	
L8/L9-S	356	3/16	0.553	0.525	0.406	0.279	0.346
L2/L3-P	357	3/16	0.519	0.612	0.517	0.527	0.575
CL/L1-P	359	3/16	0.403	0.323	0.345	0.285	0.227
L1/L2-S	359	3/16	0.48	0.221	0.415	0.44	0.319
L2/L3-P	359	3/16	0.472	0.511	0.398	0.438	0.455
L3/L4-S	359	3/16	0.456	0.433	0.221	0.127	
L4/L5-S	359	3/16	0.522	0.553	0.565	0.597	0.592
L5/L6-P	359	3/16	0.412	0.288	0.29	0.245	
L6/L7-S	359	3/16	0.452	0.517	0.444	0.425	0.372
CL/L1-P	360	3/16	0.256	0.575	0.51	0.516	0.434
CL/L1-S	360	3/16	0.415	0.251	0.231	0.217	
L1/L2-S	360	3/16	0.592	0.557	0.391	0.413	0.447
L2/L3-P	360	3/16	0.722	0.762	0.622	0.622	0.52
L3/L4-P	360	3/16	0.455	0.263	0.237	0.235	
L3/L4-S	360	3/16	0.793	0.655	0.569	0.211	
L5/L6-P	360	3/16	0.552	0.508	0.402	0.411	0.321
CL/L1-P	361	3/16	0.377	0.327	0.35	0.355	
CL/L1-S	361	3/16	0.237	0.599	0.574	0.508	0.521
L1/L2-S	361	3/16	0.209	0.341	-0.067	-0.121	
L2/L3-P	361	3/16	0.574	0.562	0.532	0.553	0.423

Table 8. (continued)

Measured between Longl's	@ Frame	Plate Size	Distortion Measurements (inches) Initial	1st Pass	2nd Pass	3rd Pass	Final
L2/L3-P	361	3/16	0.574	0.662	0.533	0.553	0.488
L3/L4-P	361	3/16	0.538	0.567	0.491	0.486	0.516
L3/L4-S	361	3/16	0.785	0.782	0.831	0.748	0.585
CL/L1-S	362	3/16	0.5	0.519	0.505	0.534	0.502
L1/L2-S	362	3/16	0.579	0.466	0.225	0.164	
L3/L4-S	362	3/16	0.996	1.026	0.862	0.787	0.596
CL/L1-P	363	3/16	0.500	0.416	0.382	0.323	
L1/L2-S	363	3/16	0.58	0.525	0.455	0.47	0.374
L2/L3-P	363	3/16	0.535	0.507	0.4	0.379	0.277
L3/L4-S	363	3/16	0.745	0.99	0.898	0.804	0.566
L6/L7-S	363	3/16	0.38	0.321	0.235	0.241	
L7/L8-P	363	3/16	0.593	0.585	0.528	0.522	0.482
CL/L1-P	364	3/16	0.562	0.519	0.431	0.384	0.335
CL/L1-S	364	3/16	0.516	0.552	0.54	0.538	0.489
L1/L2-S	364	3/16	0.479	0.409	0.285	0.23	
L2/L3-P	364	3/16	0.641	0.613	0.479	0.486	0.465
L3/L4-S	364	3/16	0.684	0.872	0.705	0.797	0.447
L4/L5-S	364	3/16	0.419	0.538	0.476	0.451	0.407
L6/L7-S	364	3/16	0.547	0.453	0.322	0.377	
L7/L8-P	364	3/16	0.675	0.591	0.533	0.515	0.44
CL/L1-P	365	3/16	0.486	0.453	0.386	0.386	0.392
CL/L1-S	365	3/16	0.453	0.476	0.44	0.443	0.453
L2/L3-P	365	3/16	0.543	0.510	0.335	0.401	0.372
L7/L8-P	365	3/16	0.416	0.411	0.246	0.355	
CL/L1-S	367	3/16	0.473	0.411	0.241	0.556	
L1/L2-P	367	3/16	0.618	0.574	0.49	0.45	0.415
L2/L3-S	367	3/16	0.391	0.386	0.336	0.33	
L3/L4-P	367	3/16	0.610	0.540	0.255	0.439	0.336
L3/L4-S	367	3/16	0.434	0.444	0.354	0.399	0.383
L6/L7-S	367	3/16	0.526	0.444	0.324	0.302	
CL/L1-S	368	3/16	0.556	0.51	0.429	0.43	0.382
L1/L2-P	368	3/16	0.746	0.746	0.538	0.554	0.411
L3/L4-P	368	3/16	0.736	[illegible]	0.594	0.533	0.521
L3/L4-S	368	3/16	0.722	0.815	0.725	0.669	0.549
L6/L7-P	368	3/16	0.438	0.466	0.364	0.348	
L6/L7-S	368	3/16	0.577	0.406	0.335	0.334	
L8/L9-P	368	3/16	0.400	0.253	0.133	0.357	
L8/L9-S	368	3/16	0.52	0.506	0.512	0.295	
CL/L1-S	369	3/16	0.445	0.395	0.347	0.347	
L1/L2-P	369	3/16	0.779	0.808	0.706	0.669	0.591
L3/L4-P	369	3/16	0.755	0.715	0.525	0.577	0.535

Table 8. (continued)

Measured between Longl's	@ Frame	Plate Size	Distortion Measurements (inches) Initial	1st Pass	2nd Pass	3rd Pass	Final
L3/L4-S	369	3/16	0.828	0.886	0.786	0.735	0.372
L5/L6-P	369	3/16	0.427	0.297	0.137	0.093	
L6/L7-S	369	3/16	0.571	0.113	0.05	0.138	
L8/L9-S	369	3/16	0.402	0.257	0.218	0.194	
L1/L2-P	370	3/16	0.823	0.867	0.763	0.716	0.649
L3/L4-P	370	3/16	0.760	0.730	0.605	0.608	0.533
L3/L4-S	370	3/16	0.835	0.886	0.768	0.738	0.512
L5/L6-P	370	3/16	0.581	0.511	0.448	0.406	0.39
L6/L7-S	370	3/16	0.582	-0.367	-0.306	-0.239	
L7/L8-P	370	3/16	0.591	0.474	0.353	0.436	0.435
L9/L10-P	370	3/16	0.437	0.366	0.254	0.24	
L1/L2-P	371	3/16	0.815	0.853	0.74	0.669	0.553
L1/L2-S	371	3/16	0.455	0.405	0.333	0.351	
L3/L4-P	371	3/16	0.654	0.549	0.414	0.425	0.38
L3/L4-S	371	3/16	0.8	0.847	0.737	0.726	0.574
L5/L6-P	371	3/16	0.687	0.596	0.518	0.426	0.323
L6/L7-S	371	3/16	0.591	0.227	0.089	0.068	
L7/L8-P	371	3/16	0.520	0.504	0.454	-0.111	
L8/L9-S	371	3/16	0.436	0.418	0.25	0.235	
L9/L10-P	371	3/16	0.413	0.368	0.214	0.306	
L10/L11-P	372	3/16	0.421	0.428	0.35	0.408	0.296
L1/L2-P	372	3/16	0.716	0.743	0.625	0.576	0.467
L1/L2-S	372	3/16	0.434	0.391	0.28	0.33	
L2/L3-P	372	3/16	0.429	0.524	0.495	0.523	0.574
L3/L4-S	372	3/16	0.507	0.516	0.398	0.381	0.33
L5/L6-P	372	3/16	0.624	0.538	0.408	0.299	
L5/L6-S	372	3/16	0.38	0.403	0.312	0.32	
L6/L7-S	372	3/16	0.572	0.464	0.371	0.373	
L8/L9-S	372	3/16	0.49	0.452	0.319	0.222	
L10/L11-P	373	3/16	0.435	0.397	0.334	0.474	0.424
L2/L3-P	373	3/16	0.426	0.591	0.324	0.56	0.425
L5/L6-P	373	3/16	0.517	0.292	0.323	0.315	
L6/L7-P	373	3/16	0.422	0.380	0.331	0.369	
L6/L7-S	373	3/16	0.52	0.469	0.446	0.397	0.313
L8/L9-P	373	3/16	0.415	0.397	0.213	0.395	0.313
L1/L2-S	375	3/16	0.401	0.406	0.208	0.192	
L2/L3-P	375	3/16	0.649	0.743	0.563	0.647	0.393
L3/L4-S	375	3/16	0.512	0.635	0.525	0.488	0.445
L5/L6-P	375	3/16	0.495	0.529	0.436	0.444	0.459
L6/L7-S	375	3/16	0.533	0.588	0.455	0.459	0.213
L7/L8-P	375	3/16	0.522	0.542	0.479	0.495	0.355

Table 8. (continued)

Measured between Longi's	@ Frame	Plate Size	Distortion Measurements (inches) Initial	1st Pass	2nd Pass	3rd Pass	Final
L8/L9-S	375	3/16	0.406	0.383	0.259	0.238	
L9/L10-P	375	3/16	0.510	0.475	0.418	0.464	0.446
CL/L1-P	376	3/16	0.485	0.417	0.325	0.344	
L1/L2-S	376	3/16	0.476	0.457	0.273	0.263	
L2/L3-P	376	3/16	0.930	1.041	0.898	0.925	0.784
L3/L4-S	376	3/16	0.657	0.659	0.595	0.616	0.539
L5/L6-P	376	3/16	0.721	0.678	0.603	0.573	0.414
L6/L7-S	376	3/16	0.742	0.676	0.504	0.446	-0.135
L7/L8-P	376	3/16	0.617	0.571	0.524	0.452	0.025
L8/L9-S	376	3/16	0.531	0.529	0.357	0.343	
L9/L10-P	376	3/16	0.316	0.424	0.127	0.26	
CL/L1-P	377	3/16	0.454	0.379	0.235	0.197	
L10/L11-S	377	3/16	0.377	0.434	0.243	0.226	
L1/L2-S	377	3/16	0.478	0.463	0.257	0.243	
L2/L3-P	377	3/16	0.953	1.068	0.929	0.937	0.662
L4/L5-S	377	3/16	0.592	0.6	0.382	0.368	0.49
L5/L6-P	377	3/16	0.797	0.732	0.668	0.607	0.378
L6/L7-S	377	3/16	0.783	0.689	0.542	0.504	0.271
L7/L8-P	377	3/16	0.616	0.572	0.463	0.536	0.372
L8/L9-S	377	3/16	0.545	0.522	0.405	0.396	0.259
L9/L10-P	377	3/16	0.466	0.441	0.129	-0.005	
CL/L1-P	378	3/16	0.457	0.409	0.209	0.261	
L10/L11-S	378	3/16	0.538	0.49	0.29	0.297	
L1/L2-S	378	3/16	0.488	0.435	0.19	0.111	
L2/L3-P	378	3/16	0.752	1.045	0.369	0.911	[illegible]
L5/L6-P	378	3/16	0.886	0.809	0.717	0.685	0.222
L6/L7-S	378	3/16	0.73	0.606	0.437	0.313	
L7/L8-P	378	3/16	0.371	0.370	0.54	0.195	
L8/L9-S	378	3/16	0.615	0.555	0.356	0.12	
CL/L1-P	379	3/16	0.535	0.497	0.327	0.3	
L10/L11-S	379	3/16	0.561	0.614	0.532	0.544	0.348
L1/L2-S	379	3/16	0.427	[illegible]	0.125	0.054	
L2/L3-P	379	3/16	0.854	[illegible]	0.332	0.31	[illegible]
L5/L6-P	379	3/16	0.709	0.541	0.751	0.722	[illegible]
L6/L7-S	379	3/16	0.725	0.646	0.472	0.23	
L8/L9-S	379	3/16	0.725	0.693	0.557	0.492	0.329
CL/L1-P	380	3/16	0.555	0.539	0.373	0.359	
L10/L11-S	380	3/16	0.785	0.751	0.591	0.595	0.422
L1/L2-S	380	3/16	0.295	0.47	0.308	0.157	
L2/L3-P	380	3/16	0.383	0.879	0.714	0.764	0.432
L5/L6-P	380	3/16	0.597	0.525	0.733	0.753	0.622

Table 8. (continued)

Measured between Longi's	@ Frame	Plate Size	Distortion Measurements (inches)				
			Initial	1st Pass	2nd Pass	3rd Pass	Final
L6/L7-S	380	3/16	0.695	0.643	0.515	0.506	0.242
L8/L9-S	380	3/16	0.666	0.649	0.487	0.488	-0.025
L10/L11-S	381	3/16	0.653	0.634	0.602	0.545	0.488
L2/L3-P	381	3/16	0.603	0.617	0.442	0.475	0.249
L3/L4-S	381	3/16	0.463	0.212	0.110	0.059	
L5/L6-P	381	3/16	0.656	0.507	0.438	0.425	0.275
L6/L7-S	381	3/16	0.500	0.491	0.392	0.397	0.269
L8/L9-S	381	3/16	0.446	0.453	0.259	0.246	
L9/L10-P	381	3/16	0.478	0.440	0.486	0.510	0.475
CL/L1-P	382	3/16	0.701	-0.075	-0.061	-0.083	

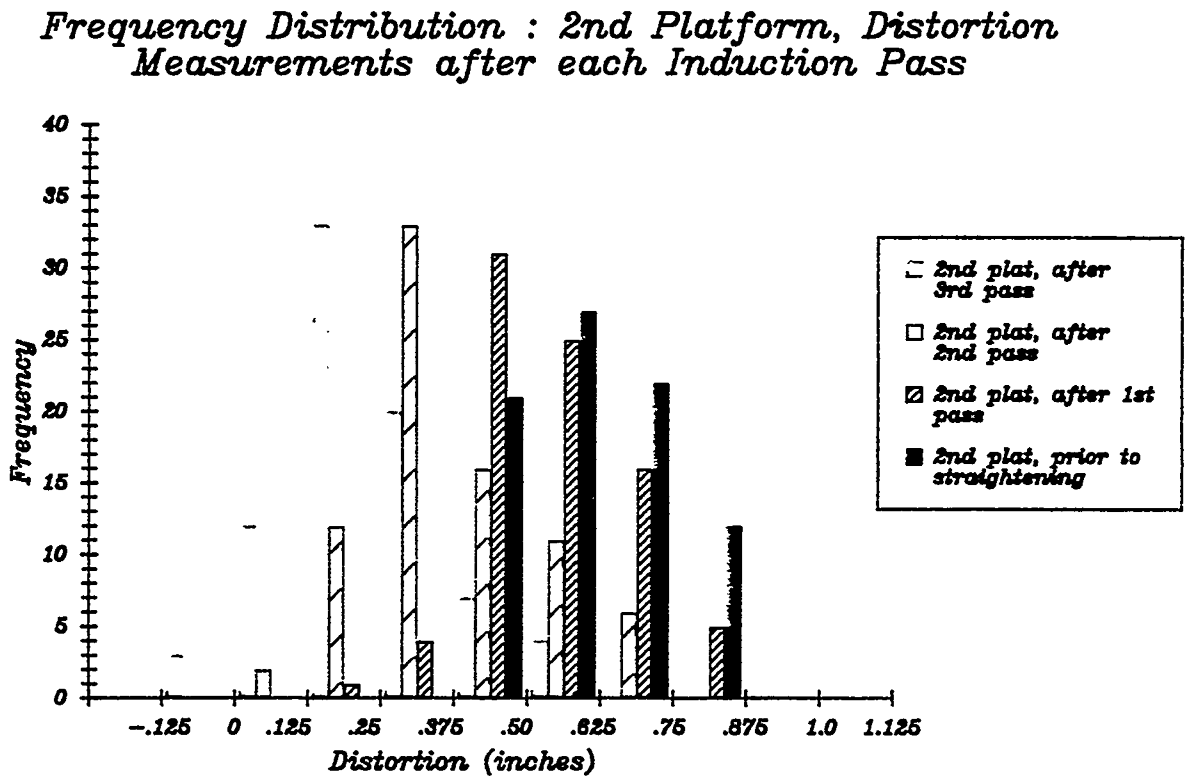
Table 9. 303 unit, 2nd platform, distortion measurements between deck longitudinal after each induction pass

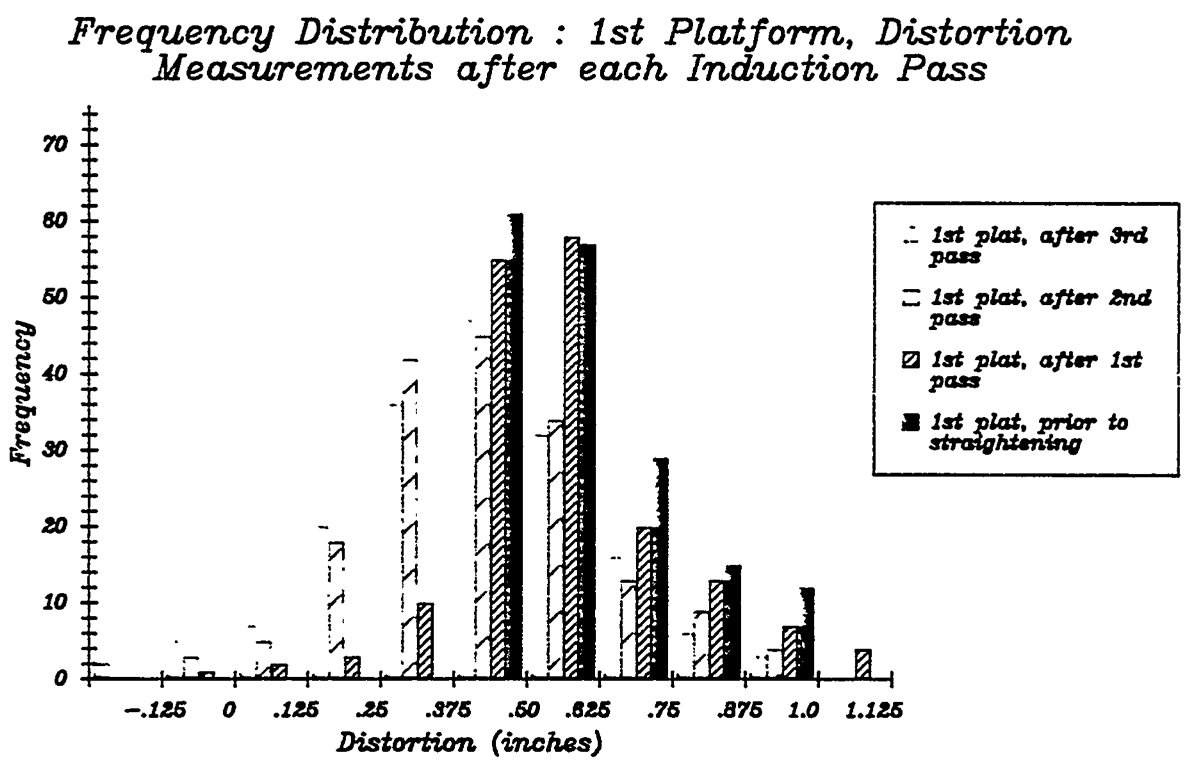
			Distortion Hmurwents (inches)				
Measured between Longl 's	@ Frame	Plate Size	Initial	1St Pass	2nd Pass	3rd pass	Final
L5/L6-P	351	1/4	0.519	0.535	0.302	0.116	
L7/L8-P	351	1/4	0.692	0.669	0.480	0.390	0.223
L7/L8-S	351	1/4	0.772	0.751	0.528	0.445	0.264
L1/L2-P	352	1/4	0.304	0.394	0.222	0.114	
L2/L3-P	352	1/4	0.487	0.483	0.362	0.234	
L3/L4-S	352	1/4	0.411	0.405	0.316	0.125	
L5/L6-P	352	1/4	0.713	0.665	0.437	0.239	
L5/L6-S	352	1/4	0.530	0.501	0.352	0.229	
L7/L8-P	352	1/4	0.834	0.786	0.709	0.581	0.261
L7/L8-S	352	1/4	0.849	0.807	0.665	0.550	0.152
L1/L2-P	353	1/4	0.337	0.445	0.240	0.130	
L3/L4-P	353	1/4	0.666	0.596	0.522	0.409	
L3/L4-S	353	1/4	0.440	0.413	0.271	0.124	
L5/L6-P	353	1/4	0.733	0.681		0.000	
L5/L6-S	353	1/4	0.541	0.506	0.359	0.210	
L7/L8-P	353	1/4	0.786	0.737	0.630	0.377	0.200
L7/L8-S	353	1/4	0.863	0.833	0.631	0.545	0.209
L1/L2-P	354	1/4	0.585	0.517	0.298	0.156	
L3/L4-P	354	1/4	0.610	0.538	0.335	0.208	
L3/L4-S	354	1/4	0.505	0.445	0.288	0.130	
L5/L6-P	354	1/4	0.706	0.668	0.328	0.233	
L5/L6-S	354	1/4	0.511	0.457	0.305	0.160	
L7/L8-P	354	1/4	0.727	0.649	0.519	0.264	
L7/L8-S	354	1/4	0.840	0.795	0.692	0.622	0.322
L3/L4-P	355	1/4	0.397	0.303	0.125	0.000	
L3/L4-S	355	1/4	0.538	0.493	0.257	0.222	
L5/L6-P	355	1/4	0.635	0.650	0.359	0.275	
L5/L6-S	355	1/4	0.508	0.460	0.219	0.156	
L7/L8-P	355	1/4	0.704	0.646	0.484	0.233	
L7/L8-S	355	1/4	0.740	0.722	0.623	[illegible]	0.372
L1/L2-P	356	1/4	0.557	0.395	0.308	0.115	
L3/L4-S	356	1/4	0.523	0.466	0.245	0.153	
L5/L6-P	356	1/4	0.585	0.584	0.102	0.000	
L5/L6-S	356	1/4	0.492	0.426	0.221	0.170	
L7/L8-P	356	1/4	0.550	0.462	0.325	0.152	
L7/L8-S	356	1/4	0.698	0.650	0.551	0.401	0.313
L2/L3-P	357	1/4	0.421	0.376	0.170	0.111	
L3/L4-S	357	1/4	0.469	0.432	0.275	0.208	
L5/L6-P	357	1/4	0.531	0.515	0.322	0.152	
L5/L6-S	357	1/4	0.423	0.395	0.271	0.153	
L7/L8-P	357	1/4	0.451	0.419	0.247	0.204	
L7/L8-S	357	1/4	0.482	0.453	0.386	0.315	

Table 9. cont nued

Measured between Longl's	@ Frame	Plate Size	Initial	1st Pass	2nd Pass	3rd Pass	Final
			Distortion Measurements inches				
L6/L7-S	359	1/4	0.381	0.389	0.292	0.263	
L3/L4-S	360	1/4	0.537	0.428	0.222	0.130	
L3/L4-S	361	1/4	0.633	0.551	0.299	0.173	
L3/L4-S	362	1/4	0.641	0.557	0.359	0.263	
L3/L4-S	363	1/4	0.629	0.519	0.333	0.216	
L6/L7-S	363	1/4	0.380	0.226			
L3/L4-S	364	1/4	0.623	0.559	0.361	0.161	
L6/L7-S	364	1/4	0.461	0.427	0.289	0.107	
L3/L4-S	365	1/4	0.497	0.467	0.340	0.161	
L6/L7-S	365	1/4	0.436	0.470	0.413	0.291	
L2/L3-P	367	5/16	0.554	0.455	0.293	0.206	
L2/L3-P	368	5/16	0.730	0.566	0.381	0.258	
CL/L1-P	369	5/16	0.493	0.423	0.260	0.158	
L2/L3-P	369	5/16	0.778	0.557	0.375	0.268	
CL/L1-P	370	5/16	0.529	0.455	0.292	0.172	
L2/L3-P	370	5/16	0.827	0.611	0.454	0.316	
L2/L3-S	370	5/16	0.472	0.469	0.395	0.323	
CL/L1-P	371	5/16	0.519	0.430	0.283	0.153	
L2/L3-P	371	5/16	0.754	0.605	0.464	0.317	
L2/L3-S	371	5/16	0.560	0.519	0.441	0.322	
CL/L1-P	372	5/16	0.481	0.402	0.255	0.118	
L2/L3-P	372	5/16	0.434	0.317	0.211	0.115	
L2/L3-S	372	5/16	0.387	0.310	0.219	0.123	
L6/L7-S	375	5/16	0.530	0.495	0.379	0.275	
L2/L3-P	375	5/16	0.686	0.641	0.295	0.150	
L3/L4-S	376	5/16	0.579	0.523	0.365	0.150	
L6/L7-S	376	5/16	0.659	0.605	0.459	0.330	
L2/L3-P	377	5/16	0.706	0.643	0.524	0.220	
L3/L4-S	377	5/16	0.619	0.551	0.397	0.130	
L6/L7-S	377	5/16	0.722	0.657	0.506	0.281	
L2/L3-P	378	5/16	0.675	0.615	0.510	0.192	
L3/L4-S	378	5/16	0.659	0.593	0.430	0.167	
L6/L7-S	378	5/16	0.743	0.621	0.512	0.291	
L2/L3-P	379	5/16	0.678	0.571	0.488	.218	
L3/L4-S	379	5/16	0.590	0.522	0.306		
• L6/L7-S	379	5/16	0.782	0.712	0.560	0.363	
L2/L3-P	380	5/16	0.629	0.566	0.509	0.332	
L3/L4-S	380	5/16	0.505	0.427	0.322		
L6/L7-S	380	5/16	0.823	0.749	0.625	0.443	0.37[illegible]
L2/L3-P	381	5/16	0.400	0.265	0.473	0.292	

Figure 76. Frequency distribution of measurements after each pass of induction unit on 1st and 2nd platforms





% of Sample Locations Out-of -Tolerance

	2nd Platform	1st Platform
prior to straightening	100.0 x	100.0 %
after 1st pass	93.9 %	90.2 %
after 2nd pass	40.2 %	60.3 %
after 3rd pass	13.4 %	59.8 %
after 4th pass	0.00 %	41.9 %

As shown, a reduction in distortion was measured after each pass of the induction unit on both platforms. The extent of this reduction, however, differed significantly between the two platforms.

On the second platform which included 0.25" and 0.313" plating, all of the out-of-tolerance locations were rorrected through four passes. In fact, 87 % were corrected through the first three passes along the deck longitudinal so that only two specific areas required a cross pattern between longitudinals, shown in Figure 77.

On the first platform, howevers although a significant amount of the out-of-tolerance locations were corrected, a reduced effect was observed in comparison to the second platform. This difference can be attributed to the large amount of 0.188" plating in the 1st platform. On this deck level, virtually no distortion reduction was observed in the third pass. Attemots to remove the distortion through the fourth pass {cross pattern) did not produce Favorable results. In this case, the induction heating produced a Very local affect that fortmed "swelled" spots in the plating. This effect was compensated for by a reductional in heat input [reduction in the span time of induction but was accompanied by reduced effeCt on distortion. Correction of the remaining out-of-tolerance locations was attempted through variations of the cross pattern (4th pass) but were similarly unsuccessful in further reducing distortion.

Another view of these same results is provided through a breakdown of the measurements for each pass by plate thickness.

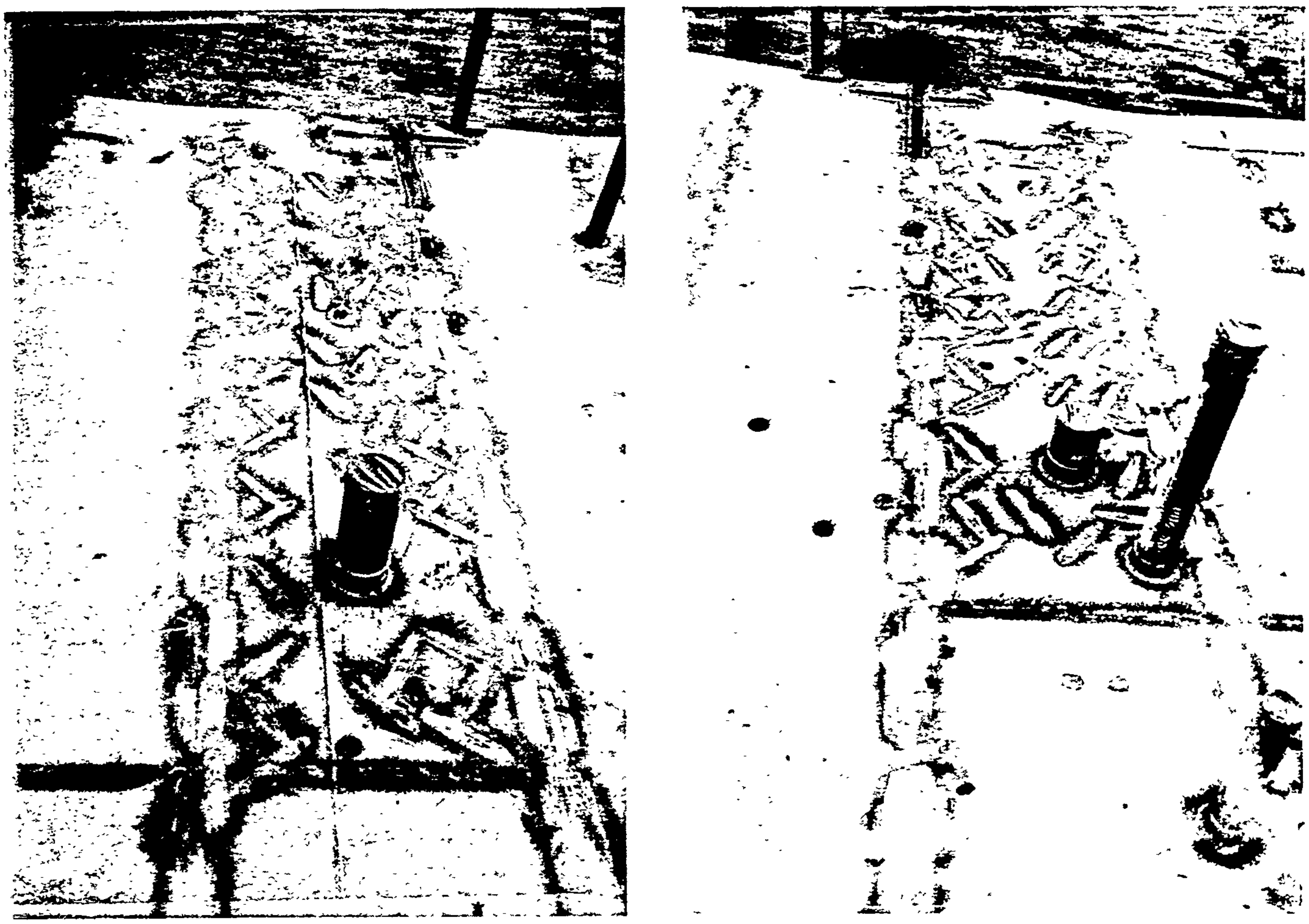


Figure 77. Cross pattern used on two 2nd platform locations still out of tolerance after three induction passes. In these locations, 100 % of the out-of-tolerance condition was corrected

Performance of each pass in terms of the percent of locations out-of-tolerance by plate thickness showed:

% of Sample Locations Out-of-Tolerance

	0.313″	0.250″	0.188″
prior to straightening	100.0 %	100.0 %	100.0 %
after 1st pass	***90.0 %***	***96.2 %***	***90.2 %***
after 2nd pass	60.0 %	30.0 %	60.3 %
after 3rd pass	3.3 %	19.2 %	59.8 %
after 4th pass	***0.0 x***	***0 . 0 %***	***41.9 %***

As shown, all distortion was brought within tolerance on the 0.25″ and 0.313″ plating through the four passes. Similar results were obtained for the first two passes on 0.188″ plating but were limited beyond that point.

14.5 Additional Observations and Comments

Use of the induction system lead to the following additional observations:

- O The induction system was simple to operate and hook-up. Uperation of the system could be learned quickly and easily.

- O Although general settings (span time of heating) are pre-established Plate thickness, Small adjustments must be made for the desired effect. The induction unit provides relatively close control over heat output.

  For example, when the pass is made directly over the longitudinal an increase in heating time is required to offset the "heat sink" effect provided by the longi- tudinal. Outside the longitudinals, a decrease can be made to obtain "surface" rather than through heating.

  Operators noted that a "feel" for heating times was quickly obtained.

- Use on flat deck areas was a one man operation. Although not attempted, operation of two induction units at a time by one person as purported by the manufacturer could be seen as difficult due to the short span time of heating at each location (normally 20-40 seconds).

- Increased difficulty was found in areas with extreme local distortion (such as where lifting lugs, hole compensation or deck drains are welded) because the induction unit could not sit flat on the deck.

- The patterns of application should be better defined to maximize the correction of distortion in the minimum number of passes. As seen in the measurements a consistently reduced effect occursd in the first pass directly over the longitudinal (approximately 5-10 % reduction in out-of-tolerance locations) as compared to succesive passes just outside the longitudinal centerline (30-50 Y, reduction) .

  Consequently, a first pass directly above the deck longitudinal (as recommended) may not be most effective when trying to correct distortion to one side only. Whole passes may be eliminated reducing the time of operation by as much as 25-33 %.

- The induction unit burned through the deck primer. Paint accumulation on the bottom of the unit had to be routinely removed.

- For areas of extreme distortion (greater than 0.354" bulge) , "jacking" of the plate into the desired Plane prior to the application of heat is recommended. This method was not tested but was observed at St. John Shipbuilding, St. John, N.B., Canada and found to be ettective, altoug costly in the level of effort and time required.

- Limitations in use of the system on bulkheads can be seen due to the weight of the induction head. A counter weight pulley system can be obtained from the

manufacturer . However, this method of use allows for only a small region to be treated before it is necessary to move the pulley system.

O Straightening efforts interior to a ship may be accomplished using an extension of the converter to induction unit cable up to a maximum length of 145' . Beyond this length, straightening efforts would be difficult. The weight of the converter, as well as its physical dimensions would create problems when trying to move the unit through watertight dnors and hatches.

15.0 Conclusion

In ship construction, with the extensive use of welding and cutting processes at nearly all stages of manufactures the added costs from distortion are substantial . These added costs are reflected not only in the straightening efforts required to remove the distortion, but also in significant increases in fitting and welding requirements. Distorted parts routinely increase the difficulty of fitup, often causing poor fitup and in some cases requiring cutback and rewelding of previously completed joints. Poorly fit parts cause overwelding, increasing welding costs and further compounding the distortion problem. As a result, the control of distortion provides a means for significantly reducing construction costs.

The successful application of distortion control rsquires a general understanding of the effects of normally incurred design and construction variables. Understanding the effects of such variables as joint location, weld sizes, sequence of assembly and welding are necessary in determining the causes and cures for distortion. Types of distortion (as well as direction) in a weldment may often be predicted and applicable control measures employed.

The selection of distortion control techniques must b= suited to the particular weldment and construction method. Not all ~echniques are useful in all situations. Similarly, no individual control technique can be singularly used to sffec-tilvely prevent distortion. For example, what good is the use of a backstep sequence if fitup accuracy is poor and overwelding is is the result? Instead, distortion control must be emphasized through each stage of the design and construction process. Design engineers, planners, craft supervisors and the craftsmen themselves must each maintain distortion control as a priority. The ii~poi-t=fic= nf ~"i-ain~'rng ***design*** and production personnel (with particular emphasis on 1st line Supervision) to anticipate distortion problems and in the appiicat ion of preventive methods should not be underestimated .

As a base approach, the control of fitup accuracy and overwelding is essential. In many shops, the emphasis on these attributes (and quality in general) is often variable with workload and the fluctuating concerns for cost and schedule performance. It has been snown that statistical process control procedures can be used to improve and then effectively control

these attributes. Routine sampling can be accomplished at minimal cost and be used to maintain a priority on fitup and welding accuracy.

In this study, a variety of methods including the use of resonant vibration during welding, presetting, weld sequencing, preheating, induction straightening and the use of water cooiing during I-beam flange stripping operations were investigated with varying results. From these efforts, further study is suggested in a number of areas, including:

- the relationship between changes in the resonant frequency and residual stress levels in a weldment
- a comparison of the effect on distortion of resanant vibration versus subresondnt vibration applied during welding operations
- the effect on resultant distortion (distinguished from residual stress levels) of various reduced weld cooiing rates
- the effect on distortion of prestraining large panels and bulkheads through use of shims during the fit and welding of stiffening longitudinals
- the overall costs of distortion; determining the costs incurred in a shipbuilding environment for the additional fitting and welding efforts required from normally achieved distortion amounts.

in summary, the control of distortion should not be perceived as simply an additional cost required to maintain quality standards, but rather as a means for improving productivity. For shipbuilding in particular, the emphasis on distortion control can be an investment with significant payback. However, unlike the upgrade of equipment or other purchasable productivity gains, the changes in methods, personnel skills and priorities as is required at each stage of design and construction will not be easily accomplished. Commitment and direction will be the inroad to the old axiom that "quality" pays off.

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appendix: Statistical Analysis of Data

To provide a further understanding of results, a brief summary of the statistical methods used is provided.

Process Variability

Variabiltiy is inherent in all manufacturing processes. Variations in personnel skill levels, wear on machinery, the quality of raw materials, environment and numerous other causes for error prevent the manufacture, no matter how carefully controlled, of the exact same product each time. Even the simplest manufacturing operations will praduce variations from design dimensions. Thus , any realistic definition of a process characteristic must include not only a mean value but the normally achieved variation from this value.

When sampling a process, a commonly used parameter known as "sample standard deviation", s, is used for quantifying this variation, and is defined by

$$s = \sqrt{\left(\frac{n}{n-1}\right)\frac{\Sigma(x-\bar{x})^2}{n}} = \sqrt{\frac{\Sigma(x-\bar{x})^2}{n-1}}$$

where X represents the average of the sample, x represents sach of the individual measurements, and n is the sample size. cans can be seen, as the variation of the individual measurements from. the mean increases, the sample standard deviation will increase.

As the size of a sample increases, the variation within the sample more closely approximates the true procsss variation: ie., the sampie standard deviation approaches the prccess standard deviation. The Factor n/(n-1) approaches the value 1, so that the process -standard devlatlan, C , is defined by

$$\sigma = \sqrt{\frac{\Sigma(x-\bar{x})^2}{n}}$$

Normal Distributions

Process samples, due to variation within the process and. to a smaller degree, variation in the measuring technique itself, will produce a "scattering" of data values. Interpretation of this variation is often accomolished through the of a "fre-s- quency distribution".

AS an example, Figure 1 provides 84 sample measurements of the variance from design width of steel panels. Figure 2 provides a frequency distribution of the data. As shown, ranges of measurement are established and the quantity of sample values that fall into each range is counted. When charted as in Figure a graphic representation of the sample distribution known as a histogram, is displayed. In this format, it can be seen that panel widths tend to vary within a specified range (0.25" short to 0.5" full) and converge around a mean value (= 0.099").

Statistical analysis is accomplished through mathematical modeling of frequency distributions. The mnst widely used distribution, and one that is often a good approximation to manufacturing processes, is known as the "normal distribution". Figure ,4 shows the normal distribution superimposed On the panel width histogram.

As seen, the normal distribution produces a "beil shaped" curve that has one important characteristic -- symmetry about ~he mean value. For this reason, the normal distribution does not provide a good approximation of skewed process distributions.

The normal distribution is defined by two parameters, the process mean (μ) and process standard deviation (σ), in the equation

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(1/2)[(x-\mu/\sigma)]^2}$$

where f(x) is the height of the normal curve at A.

The area underneath the normal curve fnr any interval o f represents the probability of occurance within that interval. To determine these probabilities for any set of /A and @ . the normal distribution eauation is expressed as the "standard normal distribution"

$$f(z) = \frac{1}{2\pi} e^{-(1/2)z^2}$$

where $z = (x-\mu/\sigma)$ = location of x in standard deviation units away from the mean.

Tables for the standard normal distribution, as shown in Figure 6, provide the area under the curve (probability) that is outside particular values of z (often described as the "z-score" parameter).

Figure 5 provides a graph of the standard normal distribution. As shown, nearly all of the area underneath the curve (99.74 %) is located within the interval nf three standard deviations from the mean. In the same manner, it can be shown that 95.44 % of the area is within two standard deviations from the mean, and 66.26 % is within one standard deviation.

As another example, suppose through repeated samples that the actual process mean for panel width accuracy was established as μ = 0.063", and that the "spread" of this accuracy was established as U = 0.150". From this definition, what percentage of panel widths could be expected to fall outside an established tolerance of +/- 0.375"?

Using μ = 0.063" and σ = 0.150", z-score values for the tolerance above (x = 0.375") and below (x = -0.375") the mean are calculated as:

$$z = (0.375 - 0.063)/0.150 \quad \text{and} \quad z = (-0.375 - 0.063)/0.150$$

$$z = 2.08 \qquad\qquad z = -2.42$$

In other words, the upper and lower tolerance limits are 2.08 and 2.92 standard deviation units away from the process mean! respectively. From the standard normal distribution table in Figure 6, it is determined that only 1.88 % and 0.18 % of the panel widths produced exceed the upper and lower tolarance limits, respectively. ,Figure 7 expresses these percentages as the area underneath the standard normal distribution curve that is outside z-score values of 2.08 and 2.92.

sampling Distributions

For any process, statistical values such as "mean" and "standard deviation" will vary from sample to sample due to the randomness associated with the sampling effort. Thus, these statistics will themselves nave a distribution, known as 3 "sampling distribution:'.

For the "mean" of a sample, its sampling distribuzi,in defined by a powerful theorem known as the "central limit theorem" . This theorem states that the ciistribution of the sample mean for large samples (usually 30 or more) from a population will be approximateiy normal -- whether the sampled population is normal or not. The mean of this sampling distribution will equal the mean of the population, μ, and will have a standard deviation, $\sigma_{\bar{x}}$, equal:

$$\sigma_{\bar{x}} = \sigma/\sqrt{n}$$

Thus , if a large number of samples of the same size, n, were taken from the same population, the mean of these samples would be normally distributed as defined by P and $\sigma_{\bar{x}}$, as shown in Figure 8.

An important use of this sampling distribution is in determining, at some predefine level of confidence, the range in which a process mean should lie. This range, known as the "confidence interval", is often expressed as a function of the z–score:

$$\bar{X} +/- Z_{\alpha/2}\,\sigma_{\bar{x}}$$

where $\bar{X}$ = the sample mean, $\sigma_{\bar{x}} = \sigma/\sqrt{n}$, and z is determined bv the desired level of confidence = $(1-\alpha)$. As shown in Figure 9, a , represents the probabiltiy of the process mean being outside the confidence interval.

As previously discussed, the table for the standard normal distribution can be used to determine the probabiltiy af occurence outside a z-score value. Reversely, the z-score value can be determined for any given value of α , or e /2,. Fo]- example, for a 95 % level of confidence α = 1-0.95 = 0.05. Since it is possible that the procsss mean occurs on either side 5: the confidence interval , Z-score vdlues at $\alpha/2$ = 0.025 are used. From Figure 6, at $\alpha/2$ = 0.025, the z-score is determined as $z_{.025}$ = 1.96. Thus , the 95 % confidence interval can be Jafinec as:

$$\bar{X} +/- (1.96)\,\sigma_{\bar{x}}$$

As an example, from the initial panel width sample of 34 measurements, within what range can the actual process mean be expected to fall with a 95 % level of confidence? From the 34 measurments, a sample mean = 0.099" and a standard deviation = 0.142" were calculated. The standard deviation of the sampling distribution, $\sigma_{\bar{x}}$, is calculated as:

standard deviation, $\sigma_{\bar{x}} = 0.142/\sqrt{84} = 0.015''$,

Thus, the 95 % confidence interval for the process mean, μ , is:

$$0.099'' +/- (1.96)(0.015'') = 0.099'' +/- 0.029''$$

In other words, the actual process mean for panel width accuracy can be expected with a 95 % level of confidence to fall within a range of -0.070” to 0.128”, as shown in Figure 10.

Testing Hypotheses about a Population Mean

In statistical testing, hypotheses are established concerning the expected outcome of the test. The outcome that the researcher wants to disprove is known as the “null hypothesis”. The hypothesis the researcher wants to establish is known as the “alternative hypothesis”.

When testing hypotheses there are two type= of error that can be made: Type I error -- where the null hypothesis is rejected by is actually true, and Type II error -- where the null hypothesis is not rejected and is actually false. The probability of Type I error occuring is usually denoted by "α". Thus, the value (1-%) is the probability of making a correct decision when the null hypothesis is false. In most cases, the value of @ is defined prior to testing in accordance with the confidence level desired in the conclusion.

As an example, what if a performance standard was appliad to the panel construction process such that mean panel widths were required to have a iess than O. 125” variance from design? From the sample taken, which produced a mean = 0.099” , could the conclusion be drawn that the process was performing within this standard? At a 95 % level of confidence?

In this case, an alternative hypothesis that states “mean panel widths are iess than 0.125 inches” is desired to be proven. To establish this assertion, a rruli hypothesis that states “mean panel widths are equal to the 0. 125 inch requirement” will attempted to be disproven:

null hypothesis, H_o : $\mu = 0.125$
alternative hypothesis, H_a : $\mu < 0.125$

Assume that mean panel widths = 0.125". As already established, if numerous samples were taken from this process, the sample means produced would vary due to the randomness associated with the sampling effort. This variation in sample mean values can be represented as a sampling distribution with a mean equa to the hypothesized process mean of 0.125". Testing of the null hypothesis is accomplished by establishing a confidence interval

within this sampling distribution. If the mean of the sample actually taken {expressed as its z-score) is outside this interval, then because af the improbability of this accurence the nulll hypotheis is rejected.

For a 95 % confidence interval, c4 = 0.05, so that from Figure 6 the interval boundary is determined as $Z_{,c5}$ = -1.645. This boundary defines the rejection region as all sample mean z-score values less than -1.645:

$$\text{rejection region,} \quad z < -1.645$$

as shown in Figure 11.

Note in this example that the 5 % rejection region is located exclusively on the left side of the sampling distribution. This is because only sample mean values less than the hypothesized mean of 0. 125" would support the alternative hypothesis. This is known as a one-sided test. If a panel width requirement was set, for example, as "equal 0" , then a two-sided test would be established as:

$$\text{null hypothesis,} \quad H_o : \quad \mu = 0$$
$$\text{alternative hypothesis!} \quad H_a : \quad \mu \neq 0$$

and at a 95 % level of confidence the rejection region would be establ i.sried as $z > z_{\alpha/2}$, where $z_{\alpha/2} = z_{.025} = 1.96$.

The z-score of the sample mean is expressed relative to the hypothesized process mean:

$$z = \frac{\bar{x} - \mu}{\sigma_{\bar{x}}} \approx \frac{\bar{x} - \mu}{s/\sqrt{n}}$$

where $\bar{x}$ = the sample mean
μ = the hypothesized process mean
and $\sigma_{\bar{x}}$ = the standard deviation of the sampling distribution, where for large n (n > 30) σ may be estimated by the sample standard deviation, s .

For this example, where the panel width sample $\bar{x}$ = 0.099",
s = 0.142" and n = 84, the z-score is calculated as:

$$z = (0.099 - 0.125)/(0.142/\sqrt{84}) = -1.678$$

Since this value falls in the rejection region z < -1.645, as shown in Figure 12, it must be conciuded that the null hypothesis is false. Thus, it can be stated with a 95 X level of confidence that panel widths have a mean variance from design that is less. than the 0.125" requirement.

RS shown, the z-score value of the sample mean may be used as a "test statistic" in drawing conclusions concerning the null hypothesis. When the z-score test statistic falls in the rejection region, as defined by the confidence interval in terms of z~ , then the null hypothesis is concluded to be false and the alternative hypothesis is true.

Testing Hypotheses about the Difference in Two Populations Means

often it is desired to compare the means of two independent samples to determine whether the populations from which they wers drawn are the same or different. This is accomplished by testing hypotheses that compare the difference in the sample means to a predefine value, such as "O".

As described previously, the sampling distribution for the sample mean of a population 'was stated to be normal for large values of n in accordance with the central limit theorem. ~,> the same manner, the sampling distribution of the difference between the means of independent samples From two populations is also normally distributed for large sample sizes.

it can be shown that the mean of this sampling distribution is the difference between the population ,means ($\mu_1 - \mu_2$), and the standard deviation is

$$\sigma_{(\bar{x}_1-\bar{x}_2)} = \sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}$$

where σ = the process standard deviation, where for large sample sizes (n > 30) σ may be approximated by the sample standard deviation, s

and n = sample size.

Testing for the difference between two populations is accomplished by establishing and attempting to disprove a null hypothesis that no difference exists between the twc population means. The alternative hypothesis states that either the difference is specifically less (or specifically greater) than zera,

requiring a one-sided test, Or simply does not equal zero, requiring a two-sided test. In some tests, a predefined value other than zero is used for the hypothesized difference between the two population means.

Testing is similar to that already accomplished for a single sample about the sampling distribution of a hypothesized population mean. The sampling distribution of the difference between the means of the two populations is defined by its two parameters: mean, $(\mu_1-\mu_2)$, and standard deviation, $\sigma_{(\bar{x}_1-\bar{x}_2)}$. Figure 13 shows this distribution as defined by these values. Then, from a predefine level of confidence (1-0(), a confidence interval within the sampling distribution may be established. The boundaries of this interval, expressed as $z_{\alpha/2}$, are determined from the table in Figure 6. Z-score values outside these boundaries form the rejection region for the null hypothesis at an α level of significance (probability for Type I errori The z-score test statistic is expressed as:

$$z = \frac{(\bar{x}_1 - \bar{x}_2) - D_o}{\sigma_{(\bar{x}_1-\bar{x}_2)}}$$

wher o the hypothesized difference oetween the population means (often equal to zero).

The confidence interval in which the difference between the two populations can be expected to fall with a $(1-\alpha)$ level of confidence is expressed as:

$$(\bar{x}_1 - \bar{x}_2) \quad +/- \quad z_{\alpha/2}\,\sigma_{(\bar{x}_1-\bar{x}_2)}$$

$$= \quad (\bar{x}_1 - \bar{x}_2) \quad +/- \quad z_{\alpha/2}\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}$$

As an example, what if a process change was made to improve the fabrication accuracy of panel widths and another sample taken to measure this improvement? If this new sample of n = 45 produced a sample mean = 0.063" variance from design width and a standard deviation = 0.125", can an improvement in mean accuracy be concluded at a 95 % level of confidence?

The test hypotheses are established as:

null hypothesis. H_o : $(\mu_1-\mu_2) = 0$
alternative hypothesis. H_a : $(\mu_1-\mu_2) > 0$

At a desired 95 % level of confidence. $\alpha = 1 - 0.95 = 0.05$. From the table in Figure 6, the z-score defining the rejection region is $z_{.05} = 1.645$. Note that this value reflects a one-sided test since only values of $(\bar{x}_1 - \bar{x}_2)$ greater than zero will support the alternative hypothesis. Thus, the rejection region for the null hypothesis is established as:

$$z > 1.645$$

Then from both samples:

initial sample, n, = **84? ~, = 0.049, and 3 = 0.142**
second sample, $n_2 = 45$, $\bar{x}_2 = 0.063$, and $s_2 = 0.125$

Calculating the z-score test statistic:

$$z = (0.099 - 0.063) \Big/ \sqrt{\frac{(0.142)^2}{84} + \frac{(0.125)^2}{45}}$$

$$z = 1.403$$

Since z = 1.403 is not greater than $z_{.05} = 1.645$ as shown in Figure 14. the null hypothesis cannot be rejected. Thus, i t must be stated that there is no indication at a 95 % level of confidence that the mean process accuracy of panel widths has improved. It must be noted that in this example, the null hypothesis is not stated to he true -- that the mean of the panel widths is the same -- because then Type 11 error would .be risked. Instead, it is simplv noted that the null hvpoche.sis must be rejected at the confidence level desired.

what if the second sample had produced a mean = 0.033" and standard deviation = 0.125"? The test statistic **is calculated as**:

$$z = (0.099 - 0.033) \Big/ \sqrt{\frac{(0.142)^2}{84} + \frac{(0.125)^2}{45}}$$

$$z = 2.723$$

Then, in this case, since the test statistic $z = 2.723$ is greater than the $z_{.05} = 1.645$, the null hvoothesis is rejected and

the alternative hypothesis accepted at an $\alpha = 0.05$ level of significance. The confidence interval in which ($\bar{x}_1 - \bar{x}_2$) can be expected to fall with a 95 % probability as shown in Figure 15, is determined as:

$$(\bar{x}_1 - \bar{x}_2) +/- Z_{\alpha/2} \sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}$$

$$= (0.099 - 0.033) +/- (1.96)\sqrt{\frac{(0.142)^2}{84} + \frac{(0.125)^2}{45}}$$

$$= 0.066 +/- 0.047$$

or specifically within the range from 0.019" to 0.113".

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Figure 1. Panel Width Measurements,
Variance from Design (in.)

0.219	-0.320	0.313	0.063	0.032	-0.094
0.313	0.063	-0.125	-0.188	0.188	0.125
0.344	0.250	0.125	0.063	0.250	-0.032
-0.032	0.250	0.188	0.063	0.157	0.000
0.188	-0.094	0.250	-0.063	0.125	0.125
0.094	0.032	0.219	0.125	0.282	-0.032
0.407	0.094	0.250	0.188	0.250	0.063
0.375	0.063	0.063	0.155	0.188	-0.063
0.250	0.063	0.125	0.063	0.063	0.032
0.000	-0.032	0.250	0.250	0.188	0.063
0.157	0.250	0.000	0.125	0.032	-0.157
0.250	0.063	0.000	0.000	-0.028	-0.313
0.063	-0.282	0.032	0.000	0.188	0.063
0.125	0.000	0.375	0.125	0.125	0.032

Figure 2. Frequency Distribution of
Panel Width Measurements

Range of Variance	Number of Measurements Within This Range
-0.501" to -0.375"	0
-0.376" to -0.250"	2
-0.251" to -0.125"	3
-0.126" to 0.000"	17
0.001" to 0.125"	32
0.126" to 0.250"	23
0.251" to 0.375"	6
0.376" to 0.500"	1
0.501" to 0.625"	0

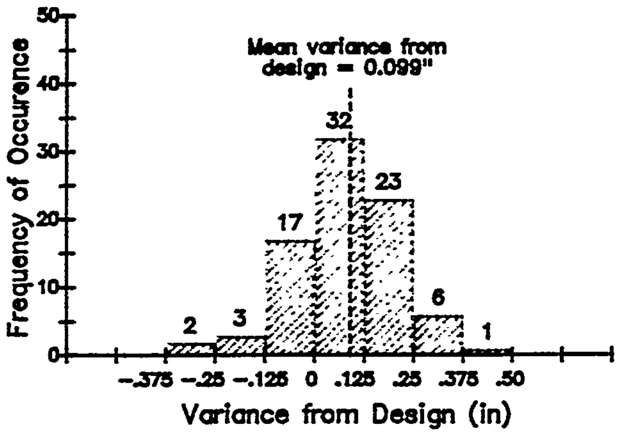


Fig 3. Panel Width Measurements, Variance from Design

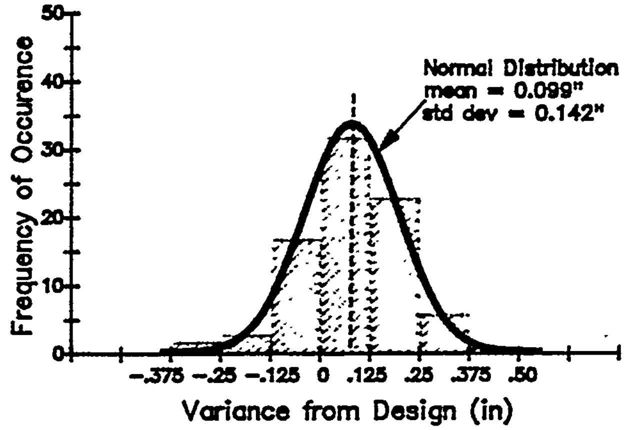


Fig. 4. Normal Distribution superimposed over Panel Widths Histogram

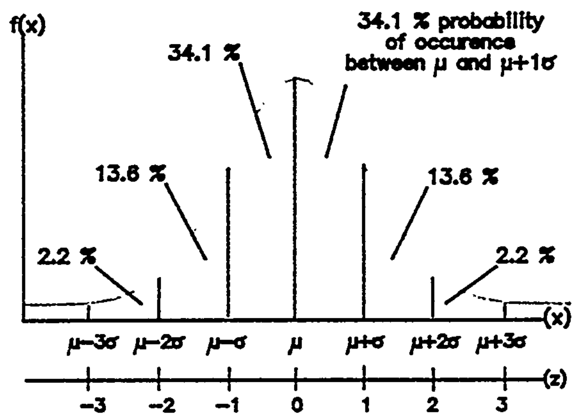


Fig. 5. Percent Area Under the Normal Distribution at μ +/− 1,2 and 3σ

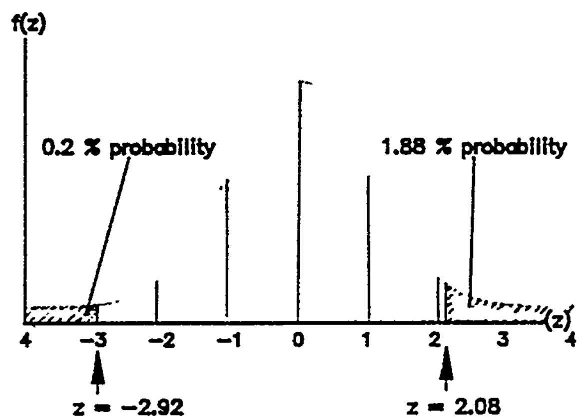


Fig. 7. Probability outside z= 2.08 and −2.92 in a Standard Normal Distribution

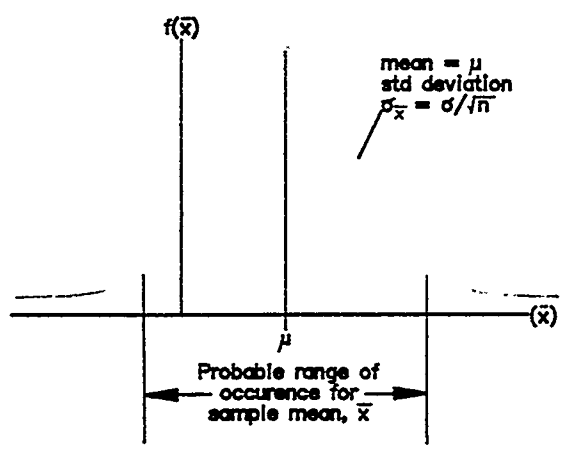


Fig. 8. Sampling Distribution for $\overline{x}$

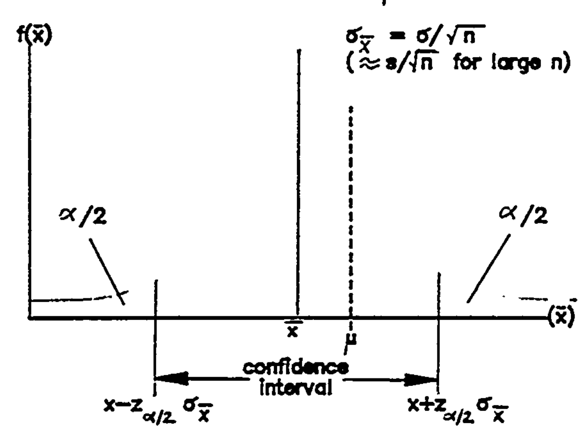
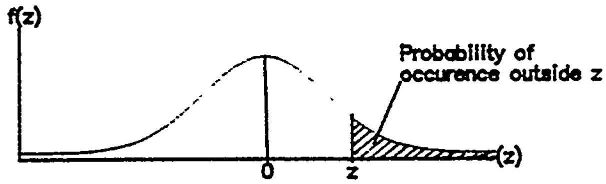


Fig. 9. Confidence Interval for Process Mean, μ

Figure 6. Area under the Standard Normal Distribution outside values of z.



|z|	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
3.0	.0014	.0013	.0013	.0012	.0012	.0011	.0011	.0011	.0010	.0010
2.9	.0019	.0018	.0018	.0017	.0016	.0016	.0015	.0015	.0014	.0014
2.8	.0026	.0025	.0024	.0023	.0023	.0022	.0021	.0021	.0020	.0019
2.7	.0035	.0034	.0033	.0032	.0031	.0030	.0029	.0028	.0027	.0026
2.6	.0047	.0045	.0044	.0043	.0041	.0040	.0039	.0038	.0037	.0036
2.5	.0062	.0060	.0059	.0057	.0055	.0054	.0052	.0051	.0049	.0048
2.4	.0082	.0080	.0078	.0075	.0073	.0071	.0069	.0068	.0066	.0064
2.3	.0107	.0104	.0102	.0099	.0096	.0094	.0091	.0089	.0087	.0084
2.2	.0139	.0136	.0132	.0129	.0125	.0122	.0119	.0116	.0113	.0110
2.1	.0179	.0174	.0170	.0166	.0162	.0158	.0154	.0150	.0146	.0143
2.0	.0228	.0222	.0217	.0212	.0207	.0202	.0197	.0192	.0188	.0183
1.9	.0287	.0281	.0274	.0268	.0262	.0256	.0250	.0244	.0239	.0233
1.8	.0359	.0351	.0344	.0336	.0329	.0322	.0314	.0307	.0301	.0294
1.7	.0446	.0436	.0427	.0418	.0409	.0401	.0392	.0384	.0375	.0367
1.6	.0548	.0537	.0526	.0516	.0505	.0495	.0485	.0475	.0465	.0455
1.5	.0668	.0655	.0643	.0630	.0618	.0606	.0594	.0582	.0571	.0559
1.4	.0808	.0793	.0778	.0764	.0749	.0735	.0721	.0708	.0694	.0681
1.3	.0968	.0951	.0934	.0918	.0901	.0885	.0869	.0853	.0838	.0823
1.2	.1151	.1131	.1112	.1093	.1075	.1056	.1038	.1020	.1003	.0985
1.1	.1357	.1335	.1314	.1292	.1271	.1251	.1230	.1210	.1190	.1170
1.0	.1587	.1562	.1539	.1515	.1492	.1469	.1446	.1423	.1401	.1379
0.9	.1841	.1814	.1788	.1762	.1736	.1711	.1685	.1660	.1635	.1611
0.8	.2119	.2090	.2061	.2033	.2005	.1977	.1949	.1922	.1894	.1867
0.7	.2420	.2389	.2358	.2327	.2296	.2266	.2236	.2206	.2177	.2148
0.6	.2743	.2709	.2676	.2643	.2611	.2578	.2546	.2514	.2483	.2451
0.5	.3085	.3050	.3015	.2981	.2946	.2912	.2877	.2843	.2810	.2776
0.4	.3446	.3409	.3372	.3336	.3300	.3264	.3228	.3192	.3156	.3121
0.3	.3821	.3783	.3745	.3707	.3669	.3632	.3594	.3557	.3520	.3483
0.2	.4207	.4168	.4129	.4090	.4052	.4013	.3974	.3936	.3897	.3859
0.1	.4602	.4562	.4522	.4483	.4443	.4404	.4364	.4325	.4286	.4247
0.0	.5000	.4960	.4920	.4880	.4840	.4801	.4761	.4721	.4681	.4641

*** Ref 5.

Fig. 10. 95% Confidence Interval for $\overline{x}$ = 0.099" and $\sigma_{\overline{x}}$ = 0.015"

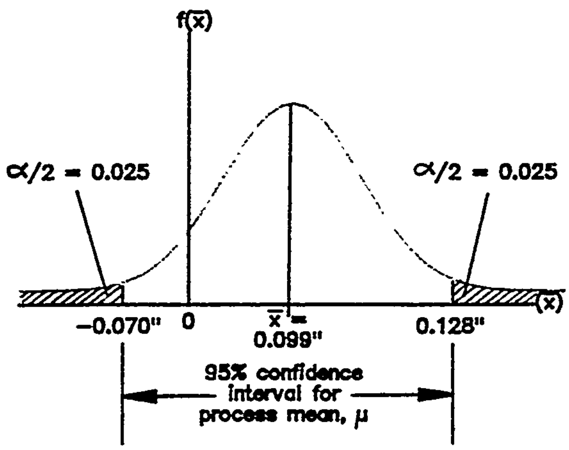


Fig. 11. 5% Rejection Region in Sampling Distribution

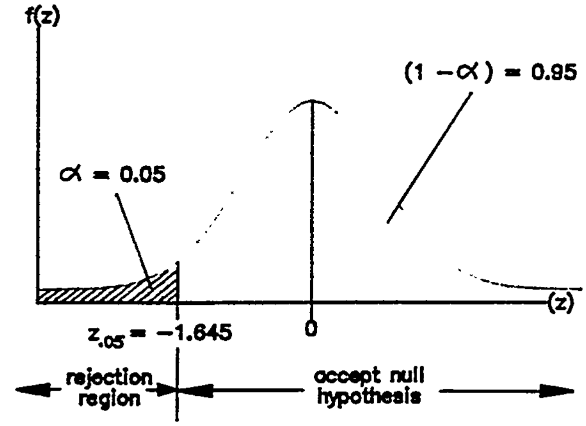


Fig. 12. z = −1.648 in Rejection Region of Sampling Distribution

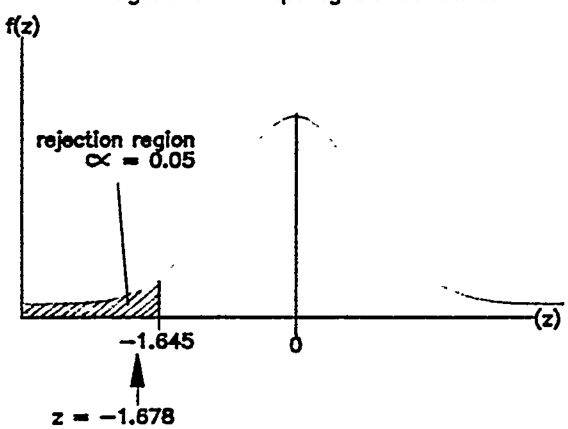


Fig. 13. Sampling Distribution of ($\overline{x}_1$ − $\overline{x}_2$)

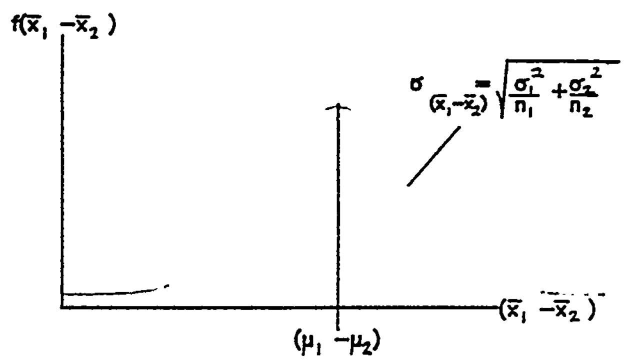


Fig. 14. z = −1.403 not in Rejection Region of Sampling Distribution

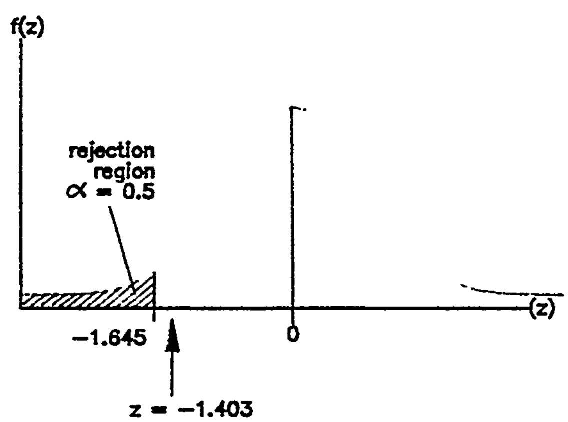


Fig. 15. 95% Confidence Interval for ($\overline{x}_1$ −$\overline{x}_2$)